National Institute of
BUILDING SCIENCES

Natural Hazard Mitigation Saves:
2017 Interim Report

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NOTE: All currency figures are in 2016 U.S. dollars unless otherwise noted. Benefits and costs are rounded to no more than two significant figures to reduce the appearance of excessive accuracy. Unless otherwise indicated, benefits and costs are calculated based on a 2.2% discount rate.

Cover Photo: Marathon, Florida – These modern, mitigated homes withstood Hurricane Irma. They are elevated to withstand high water and their roofs are constructed to withstand up to 220 mph winds. Good mitigation learns from mistakes to build more-resilient communities. (Photo by Howard Greenblatt/FEMA/November 22, 2017)

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National Institute of BUILDING SCIENCES

Natural Hazard Mitigation Saves:
2017 Interim Report

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Prepared by the
National Institute of Building Sciences
Multihazard Mitigation Council

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About the National Institute of Building Sciences

The National Institute of Building Sciences (Institute), authorized by public law 93-383 in 1974, is a nonprofit, nongovernmental organization that brings together representatives of government, the professions, industry, labor and consumer interests to identify and resolve building process and facility performance problems. The Institute serves as an authoritative source of advice for both the private and public sectors with respect to the use of building science and technology.

About the Multihazard Mitigation Council

The Multihazard Mitigation Council (MMC) serves as a focal point of credible information to inform decision-making to overcome a number of real-world barriers to implementing disaster resilience and mitigation measures in the United States. The MMC promotes collaboration among homeowners, commercial and industrial property owners, researchers, finance and insurance representatives, the public sector, and many others to achieve resilience objectives.

For further information on the Institute and MMC activities and products, see the Council's webpage (www.nibs.org/mmc) or contact the Multihazard Mitigation Council, National Institute of Building Sciences, 1090 Vermont, Avenue, N.W., Suite 700, Washington, D.C. 20005; phone 202-289-7800; fax 202-289-1092.

Foreword

More than a decade ago, the National Institute of Building Sciences released a study, *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*, which found society saves $4 for every $1 spent on mitigation by the Federal Emergency Management Agency.

In the years since, the United States has experienced some of the most devastating disasters in the country's history. Just four of the major disasters that have occurred in 2017—Hurricanes Harvey, Irma, and Maria, and the extensive wildfires in California—will likely represent some of the highest collective losses from natural disasters in any year since the founding of the nation. Future disasters are inevitable, yet their growing frequency and magnitude of destruction are substantially exacerbated by the decisions Americans make in where and how they build. The populations of cities and communities continue to grow in hazard-prone areas. Unless something is done to change the course of destruction, future events will affect more lives, businesses, and the U.S. economy as a whole.

Despite the widely publicized impacts of disasters such as Hurricanes Katrina and Sandy, the funding for mitigation has declined over the years, even if the risks clearly have not. Just as financial advisors tell anyone planning their financial future (whether preparing for their kids' college education, buying a house, or saving for retirement) to start saving long in advance, we as a nation must also prepare and plan for future events. U.S. communities and individuals need to be ready for potential hazardous events that, though they might not arrive until long into the future, will be all too real when they strike, and have the potential to impact lives for months and possibly years.

Pre-disaster mitigation—preparing in advance for future disasters—better assures that hazardous events will have short-lived and more manageable outcomes. Mitigation saves lives, preserves homes and belongings, reduces the need for temporary shelter; helps economies to spring back faster, and lowers recovery costs. At the same time, investing in mitigation invigorates the economy through increased construction—whether the funding comes through federal or state programs, or through privately financed retrofits and new construction.

Building on the goals of the 2005 *Mitigation Saves* study, this report, *Natural Hazard Mitigation Saves: 2017 Interim Report*, shares the results from the first of a multi-year project. The purpose of this new study is to help decision-makers to build a mitigation strategy so they can protect lives, property, and assets. The findings are intended to inform future code changes to make communities more resilient, help jurisdictions make decisions on what codes to adopt and enforce, and assist policymakers in developing effective federal programs that support pre-disaster mitigation. This report and the underlying study represent the work of an expert project team, which was vetted by an equally qualified oversight committee and received feedback from building industry stakeholders and federal government reviewers, all of which are acknowledged at the end of the report.

We thank the key stakeholder organizations identified on the title page that have provided financial support for this first round of results. However, additional work is needed to assess a broad suite of mitigation strategies. We hope you will consider supporting this project moving forward.

The National Institute of Building Sciences encourages the president; members of the U.S. Congress and state legislatures; leaders of federal and state agencies; and community leaders to review this report and use the results when making decisions to develop more-resilient communities that can withstand the disasters that will inevitably come. The Institute also encourages members of the building industry to consider this document when developing future codes and standards to help make commercial and residential buildings more resilient in disaster-prone regions of the United States.

I am proud to present this *2017 Interim Report*, and look forward to sharing the final product in the months to come.

Sincerely,

Henry L. Green, Hon. AIA
President

Table of Contents

Index of Figures

Index of Tables

Natural Hazard Mitigation Saves:
2017 Interim Report

Summary of Findings

Federal Mitigation Grants Save $6 per $1 Spent, Exceeding Codes Saves $4 per $1 Spent

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants, and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, and preventing property loss and disruption of day-to-day life.

Given the rising frequency of disaster events and the increasing cost of disaster recovery across the nation, mitigation actions are crucial for saving money, property, and, most importantly, lives. Activities designed to reduce disaster losses also may spur job growth and other forms of economic development.

Mitigation represents a sound financial investment. This Interim Study examined two sets of mitigation strategies and found that society saves $6 for every $1 spent through mitigation grants funded through select federal agencies and a corresponding benefit-cost ratio (BCR) of 4:1 for investments to exceed select provisions of the 2015 model building codes.

Just implementing these two sets of mitigation strategies would prevent 600 deaths, 1 million nonfatal injuries, and 4,000 cases of post-traumatic stress disorder (PTSD) in the long term. In addition, designing new buildings to exceed the *2015 International Building Code* (IBC) and *International Residential Code* (IRC), the model building codes developed by the International Code Council (also known as the I-Codes) would result in 87,000 new, long-term jobs, and an approximate 1% increase in utilization of domestically produced construction material.[1]

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	6:1	4:1
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

[1] Higher construction costs might also cost jobs if they make new homes less affordable, unless the higher cost of homes is offset by incentives as described in the section, "Incentivization Can Facilitate Ideal Levels of Investment."

The Interim Study examined four specific natural hazards: riverine and coastal flooding, hurricanes, earthquakes, and fires at the wildland-urban interface (WUI). The national-level benefit-cost ratios (BCRs) aggregate the study findings across these natural hazards and across state and local BCRs. Table 1 provides BCRs for each natural hazard the project team examined.

This work quantifies many, but not all, of the important benefits of mitigation. Mitigation activities save more than what is estimated in this report. Disasters disconnect people from friends, schools, work, and familiar places. They ruin family photos and heirlooms and alter relationships. Large disasters may cause permanent harm to one's culture and way of life, and greatly impact the most socially and financially marginal people. Disasters may have long-term consequences to the health and collective well-being of those effected. Such events often hurt or kill pets and destroy natural ecosystems that are integral parts of communities. Disasters clearly disrupt populations in ways that are difficult to articulate, let alone assign monetary worth.

This Interim Study updates and expands a 2005 study conducted by the National Institute of Building Sciences (Institute) Multihazard Mitigation Council (MMC), at the direction of the U.S. Congress, entitled *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities* (the 2005 study), which found, among other things, that every $1 of natural hazard mitigation funded by the Federal Emergency Management Agency (FEMA) between 1993 and 2003 saved the American people an average of $4 in avoided future losses.[2]

The 2017 Study provides an updated examination of the benefits of federal agency grant programs. It utilizes a more-realistic economic life span for buildings (75 versus 50 years) and takes advantage of a more-advanced Hazus-MH flood model and improvements in FEMA's Benefit-Cost Analysis Tool, which, among other things, allows quantification of the benefit associated with enhanced service to the community provided by fire stations, hospitals, and other public-sector facilities. The 2005 study did not estimate the economic costs associated with PTSD. The 2005 study also did not calculate avoided insurance administrative costs, overhead, and profit, the reduction of which can add significant benefit in some situations. The ability to estimate urban search and rescue costs is introduced here.

Mitigation Strategies Studied

The Institute's MMC undertook a study to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. The 2017 Interim Study analyzes two sets of mitigation strategies:

Federal grants: The impacts of 23 years of federal mitigation grants provided by FEMA, the Economic Development Administration (EDA), and Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.

Beyond code requirements: The costs and benefits of designing all new construction to exceed select provisions in the *2015 International Building Code* (IBC) and the *2015 International Residential Code* (IRC) and the implementation of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

[2]National Institute of Building Sciences. *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities* (2005). http://www.nibs.org/mmc_projects#nhms

BCRs in Greater Depth

The Interim Study examines the savings (benefit) associated with an identified level of investment (cost). The ratio of the former to the latter is the BCR, which is one of many measures that decision-makers can use to judge the desirability of an investment. Here, "cost" means the up-front construction cost and long-term maintenance costs to improve existing facilities or the additional up-front cost to build new ones better. "Benefit" refers to the present value of the reduction in future losses that mitigation provides. For the results presented in this report, a discount rate of 2.2% is used. At higher discount rates (including those used by the Office of Management and Budget), such measures remain cost-effective.[3]

The 2017 Interim Study includes the benefits associated with avoided cases of PTSD. The project team considered the cost of mental health impacts similarly to costs related to injuries as a whole; that is, as an acceptable cost to avoid a future statistical injury, as opposed to the expense associated with a particular injury. The costs consider direct treatment costs where treatment is about 10% of the overall costs of the incidence, and the other costs include things like lost wages, lost household productivity, and pain and suffering. Because few benefit cost analyses (BCAs) even attempt to include these costs, the addition of acceptable costs to avoid a statistical instance of PTSD is a conservative but innovative addition to the 2017 *Mitigation Saves* study.[4]

Why Two BCRs?

This *Interim Report* of results features two high-level BCRs representing the benefits of mitigation achievable by exceeding code provisions and through federal grant programs. While the project team recognizes the desire to have a single BCR that would facilitate widespread dissemination of the project results, providing such an aggregate number will be more useful when other parts of the *Mitigation Saves* study are completed.

The 2005 study produced the widely cited results that showed a $4 benefit for every $1 invested in mitigation. Despite the specific guidance that the result represented only a single, very narrow set of mitigation strategies, specifically those funded through FEMA mitigation grants, the BCR has been used to justify all types of mitigation strategies. The *2017 Interim Report* provides an updated examination of the benefits of federal agency grant programs (including the addition of EDA and HUD), resulting in a $6 benefit for every $1 invested. While not a direct replacement, when used to describe federal grant programs, the 6:1 BCR can be used in place of the original 4:1.

The *2017 Interim Report* also includes the results from the examination of a new set of mitigation measures: exceeding the 2015 IBC and IRC and implementing the 2015 IWUIC. These strategies provide an aggregate benefit of 4:1. While these mitigation measures are an important addition to the dialogue around mitigation, they still only represent a subset of many practical strategies.

In lieu of providing a result based on a limited set of mitigation measures, with the result likely to change as new mitigation strategies are studied and added to the aggregate number, the project team elected to provide BCRs for each strategy individually. Once the project team has identified BCRs for a sufficient number of mitigation strategies, it will provide an aggregated number representing the overall benefit of mitigation.

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[3]Consult Section 2.9 in the full report for an in-depth discussion on discount rates.

[4]See Sections 3.7 and 4.17 of the Technical Documentation for an in-depth discussion on the calculation of PTSD.

Figure 1 shows the overall ratio of costs to benefits for identified federal agency mitigation programs. Figure 2 shows the overall ratio of benefits to costs of designing new buildings to exceed the select I-Code requirements that the project team studied. The costs reflect only the added cost relative to the 2015 IBC and IRC. Where communities have an older code or no code in place, additional costs and benefits will accrue.

Figures 1 and 2 show that benefits extend beyond the property lines of the mitigated buildings and the lives of occupants. Mitigation frees up resources that would otherwise be spent on insurance claims and administrative fees. Mitigation helps to assure critical post-disaster services to the community (e.g., fire stations and hospitals). Benefits and costs are rounded to no more than two significant figures to reduce the appearance of excessive accuracy.

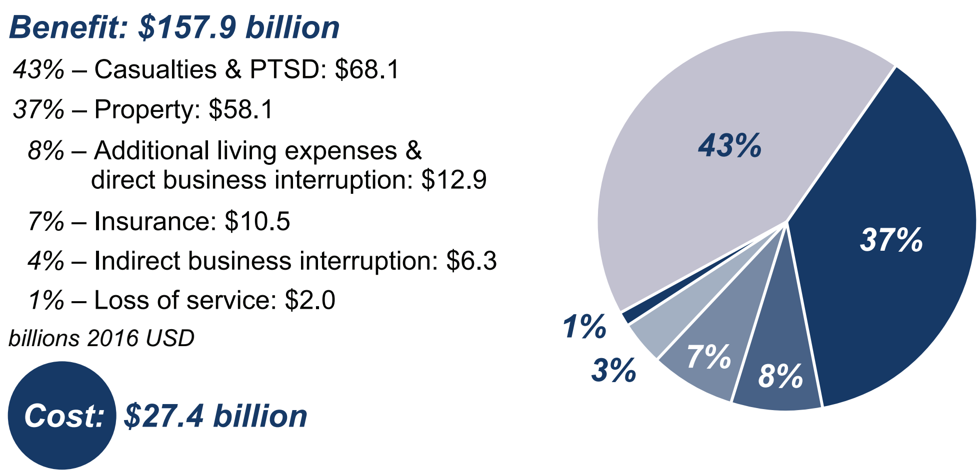

Figure 1. Total costs and benefits of 23 years of federal mitigation grants.

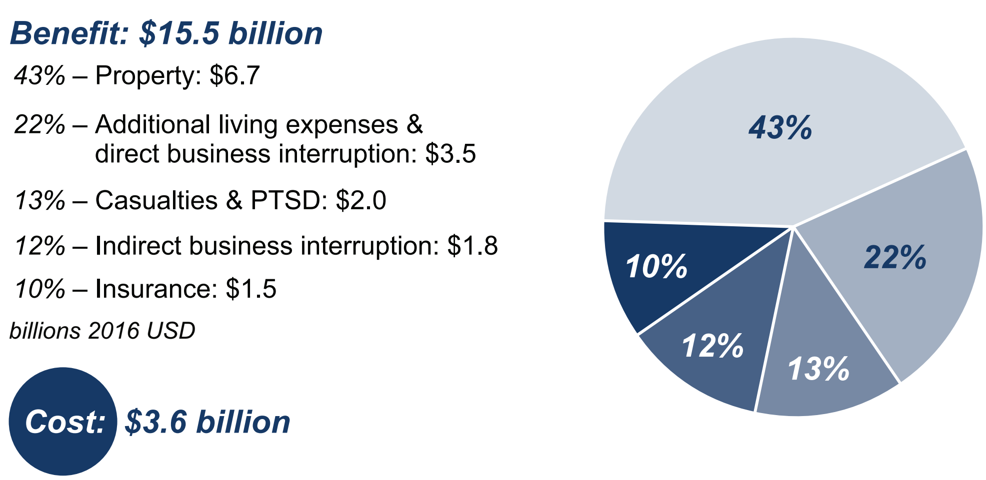

Figure 2. Total costs and benefits of new design to exceed 2015 I-Code requirements.

Tables 2 and 3 provide details on the costs and benefits. The costs would be experienced mostly at the time of construction.

Mitigation Category	Cost	Benefit	BCR
Riverine Flood	$11.51	$82.00	**7:1**
Wind	$13.60	$70.00	**5:1**
Earthquake	$2.20	$5.70	**3:1**
Wildland-Urban Interface Fire	$0.06	$0.17	**3:1**
Total for federal grants	**$27.40**	**$157.90**	**6:1**

Table 2. Costs and benefits associated with 23 years of federal grants (in $ billions).

Mitigation Category	Cost	Benefit	BCR
Riverine Flood	$0.91	$4.30	**5:1**
Hurricane Surge	$0.01	$0.05	**7:1**
Hurricane Wind	$0.72	$3.80	**5:1**
Earthquake	$1.20	$4.30	**4:1**
Wildland-Urban Interface Fire	$0.80	$3.00	**4:1**
Total for select measures to exceed I-Code requirements	**$3.60**	**$15.50**	**4:1**

Table 3. Costs and benefits associated with constructing new buildings in one year to exceed 2015 I-Code requirements (in $ billions).

Mitigation Benefits at the State and Local Level

Just as the vulnerability to specific natural hazards varies geographically, so too does the BCR for specific mitigation measures to resist those natural hazards. Figures 3 through 7 identify the state- or county-specific BCRs for designing to exceed select I-Code requirements. Considering the past 23 years of federally-funded mitigation grants, every state in the contiguous United States is estimated to realize at least $10 million in benefits, with the majority of states exceeding $1 billion in benefits. Four states: Louisiana, New Jersey, New York, and Texas, will save at least $10 billion (Figure 7).

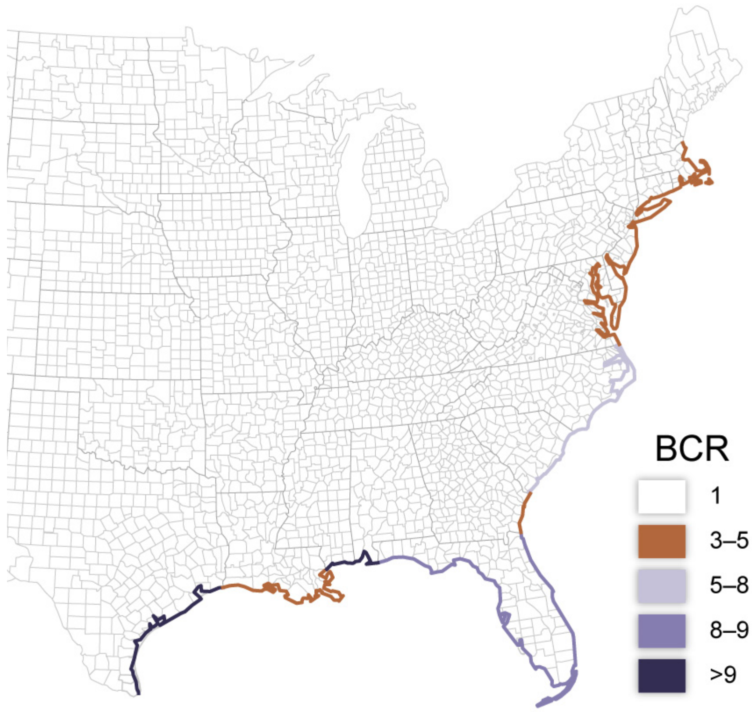

Figure 3. BCR of coastal flooding mitigation by elevating new homes above 2015 IRC requirements (by state).

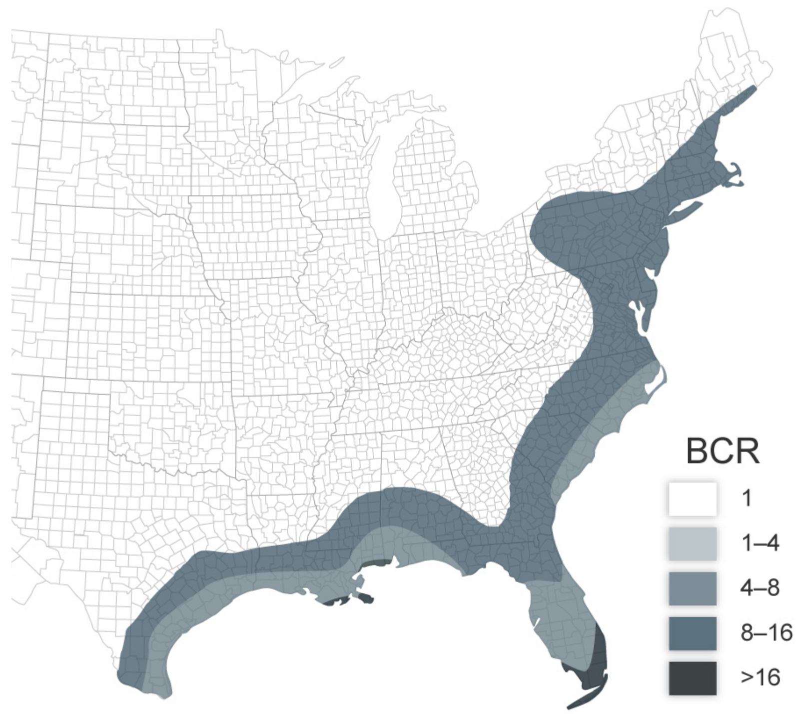

Figure 4. BCR of hurricane wind mitigation by building new homes under the FORTIFIED Home Hurricane Program (by wind band).

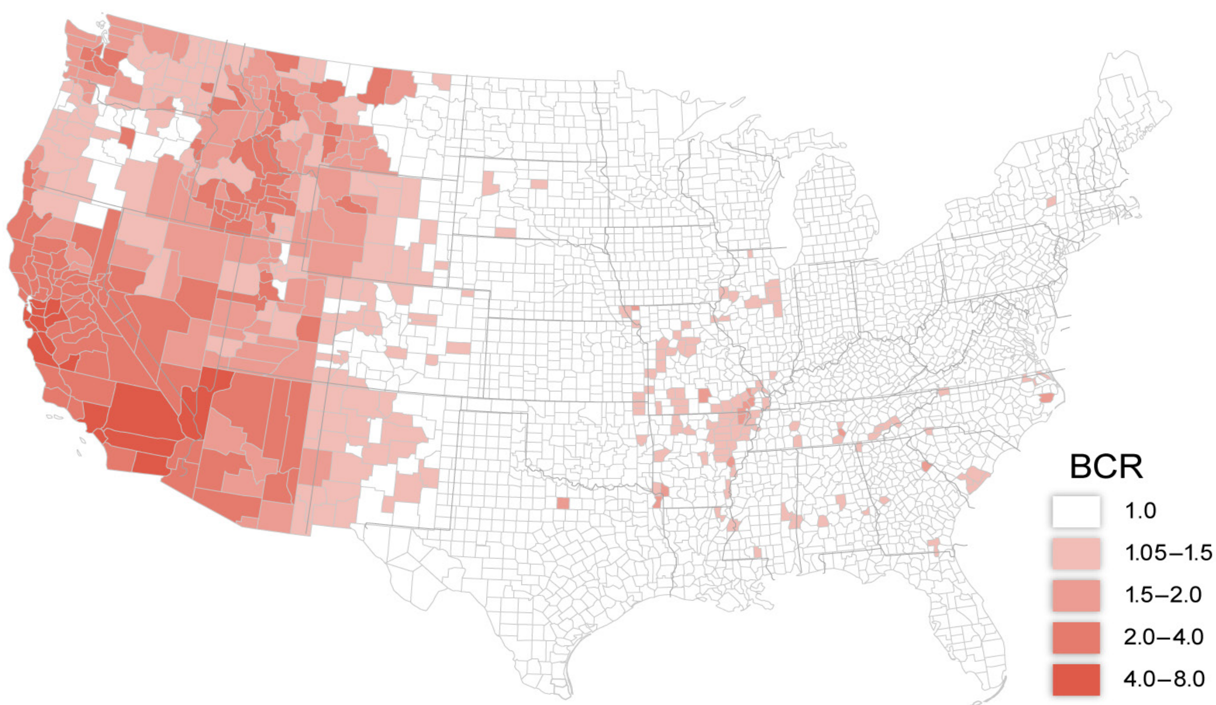

Figure 5. BCR of earthquake mitigation by increasing strength and stiffness in new buildings (by county).

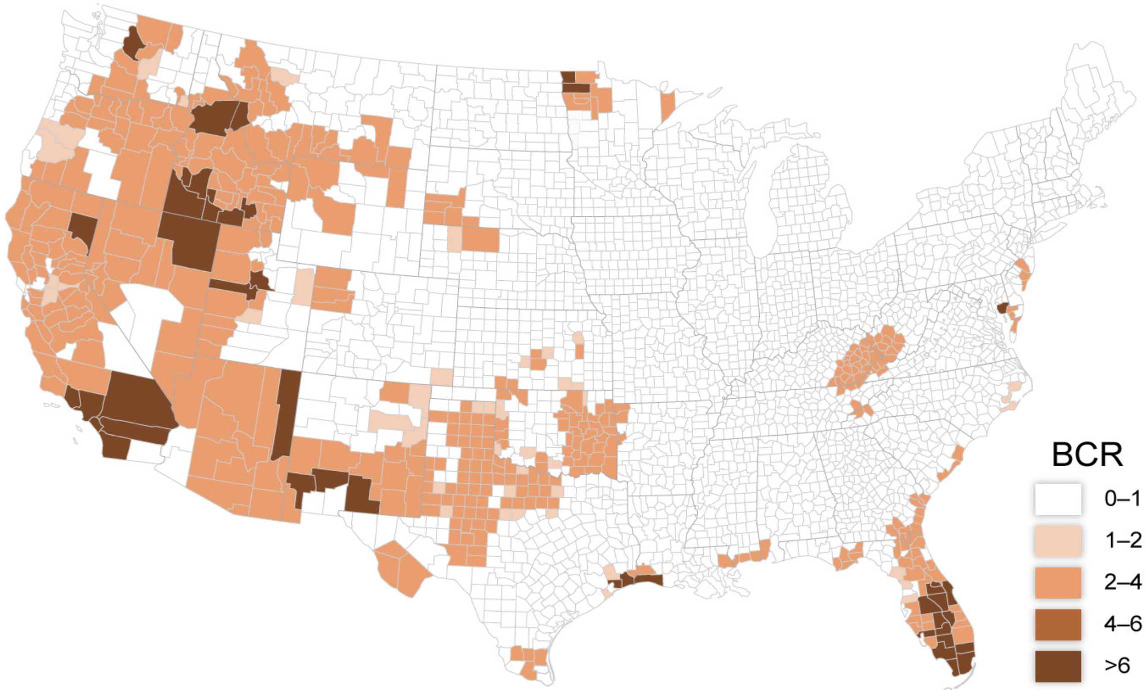

Figure 6. BCR of WUI fire mitigation by implementing the 2015 IWUIC for new buildings (by county).

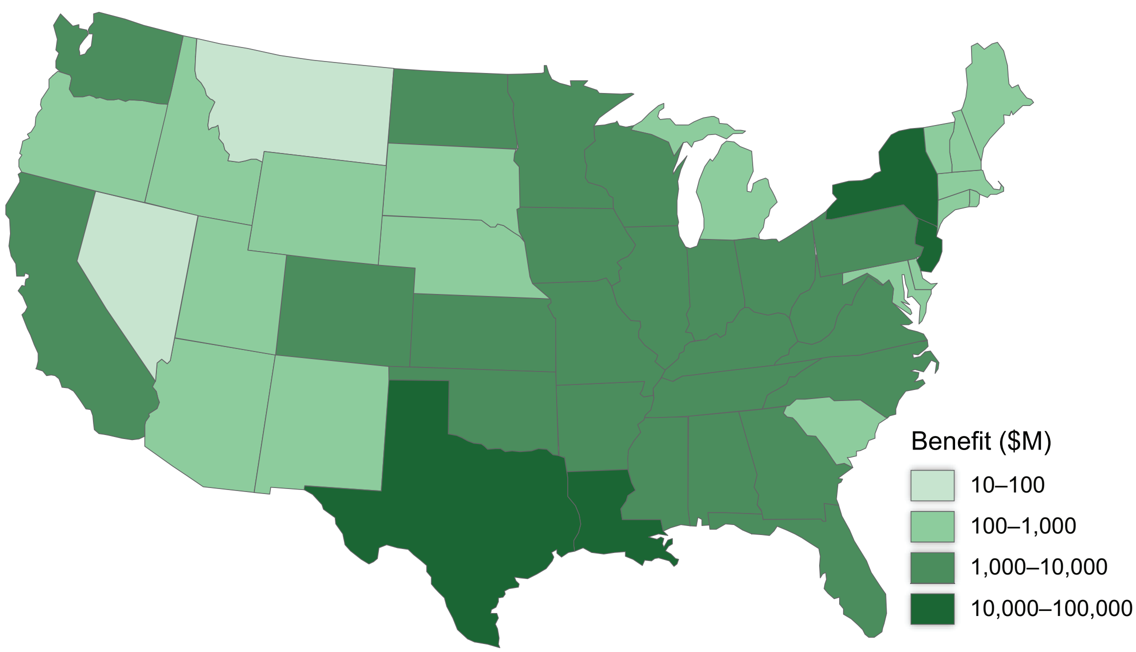

Figure 7. Aggregate benefit by state from federal grants for flood, wind, earthquake, and fire mitigation.

Building on the 2005 Mitigation Saves Study

In recent years, with the growing interest in the concept of resilience and the rising costs of disaster recovery, the MMC and industry stakeholders contemplated updating and expanding the 2005 study to address hazard-mitigation investments made by additional federal agencies, examine fire at the wildland-urban interface, and examine mitigation measures undertaken by the private sector.

In 2017, the Institute, through a team of researchers, began a new, multi-year effort to develop an updated and expanded look at the benefits of hazard mitigation. This 2017 *Interim Report* includes the results from the study of two sets of mitigation measures. This *Summary of Findings* is the first of multiple documents that will ultimately examine the value of many kinds of natural hazard mitigation at the national level. The mitigation measures discussed are described in detail in the *Technical Documentation.*

Mitigation Measures Studied

The 2017 Interim Study uses the same independent, transparent, peer-reviewed methods from the 2005 study. Where practical, the 2017 study advances the prior work utilizing newer or more effective techniques.

The federal agency strategies consider 23 years of public-sector mitigation of buildings funded through FEMA programs, including the Flood Mitigation Assistance Grant Program (FMA), Hazard Mitigation Grant Program (HMGP), Public Assistance Program (PA), and Pre-Disaster Mitigation Grant Program (PDM), as well as the HUD Community Development Block Grant Program (CDBG) and several programs of the EDA. Barring identification of additional federal data sets or sources of federal mitigation grant and loan funding, these analyses represent essentially a comprehensive picture of such mitigation measures. In the future, the project team might also look at mitigation measures directly implemented by federal agencies.[5] Results represent an enhanced and updated analysis of the mitigation measures covered in the 2005 study.

This Interim Study quantified a number of benefits from mitigation, including reductions in:

- Future deaths, nonfatal injuries, and PTSD.
- Repair costs for damaged buildings and contents.
- Sheltering costs for displaced households.
- Loss of revenue and other business-interruption costs to businesses whose property is damaged.
- Loss of economic activity in the broader community.
- Loss of service to the community when fire stations, hospitals, and other public buildings are damaged.
- Insurance costs other than insurance claims.
- Costs for urban search and rescue.

[5]Such measures include U.S. Army Corp of Engineers levees and other water management programs; National Oceanic and Atmospheric Administration early warning systems for weather; and U.S. Department of Agriculture (USDA) Forest Service prescribed burns.

Public-sector mitigation strategies include:

- For flood resistance, acquire or demolish flood-prone buildings, especially single-family homes, manufactured homes, and 2- to 4-family dwellings.
- For wind resistance, add hurricane shutters, tornado safe rooms, and other common measures.
- For earthquake resistance, strengthen various structural and nonstructural components.
- For fire resistance, replace roofs, manage vegetation to reduce fuels, and replace wooden water tanks.

The project team considered the benefits that would result if all new buildings built in one year were designed to exceed select I-Code requirements where it is cost-effective to do so. If accomplished, the benefits would be that much greater, in proportion to this quantity of new buildings. The stringency of codes adopted at the state and local level varies widely. To set a consistent starting point, the project team used the unamended 2015 IBC and IRC as the baseline minimum codes for this study. While minimum codes provide a significant level of safety, society can save more by designing some new buildings to exceed minimum requirements of the 2015 IBC and IRC and to comply with the 2015 IWUIC in others. Strategies to exceed minimum requirements of the 2015 I-Codes studied here include:

- For flood resistance (to address riverine flooding and hurricane surge), build new homes higher than required by the 2015 IBC.
- For resistance to hurricane winds, build new homes to comply with the Insurance Institute for Business & Home Safety (IBHS) FORTIFIED Home Hurricane standards.
- For resistance to earthquakes, build new buildings stronger and stiffer than required by the 2015 IBC.
- For fire resistance in the wildland-urban interface, build new buildings to comply with the 2015 IWUIC.

Multiple Stakeholders Benefit from Above-Code Design

Designing new buildings in some places to exceed select 2015 IBC and IRC requirements, and designing new buildings in parts of the WUI to better resist fire, affects various stakeholder groups differently. The project team considered how each of five stakeholder groups bears the costs and enjoys the benefits of mitigation for the four natural hazards under consideration. Stakeholders include:

- Developers: Corporations that invest in and build new buildings, and usually sell the new buildings once they are completed, owning them only for months or a few years.
- Title holders: People or corporations, who own existing buildings, generally buying them from developers or from prior owners.
- Lenders: People or corporations that lend a title holder the money to buy a building. Loans are typically secured by the property, meaning that if the title holder defaults on loan payments, the lender can take ownership.
- Tenants: People or corporations, who occupy the building, whether they own it or not. This study uses the term "tenant" loosely, and includes visitors.
- Community: People, corporations, local government, emergency service providers, and everyone else associated with the building or who does business with the tenants.

When one subtracts the costs each group bears from the benefits it enjoys, the difference—called the net benefit—is positive in each category. Figure 8 reflects long-term averages to broad groups, so it only speaks to the group as a whole, on average, rather than to the experience of each individual member of the group.

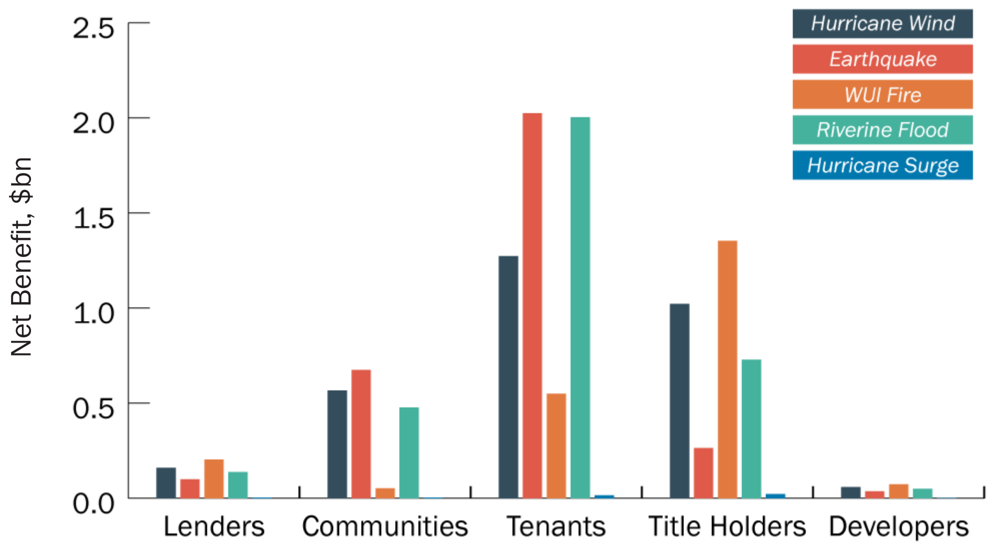

Figure 8. Stakeholder net benefits resulting from one year of constructing all new buildings to exceed select 2015 IBC and IRC requirements or to comply with 2015 IWUIC.

Additional Mitigation Measures

The mitigation measures analyzed by the project team represent only some of the measures that could ultimately be applied to address the natural hazards studied. Recognizing the current limited applicability of the data provided, the project team identified additional mitigation measures to be studied. Some will be evaluated in 2018, while others have been identified but their analysis remains unfunded.

Because some jurisdictions have no codes or older codes in place, many buildings within their communities have limited protection from natural hazards. When considering whether to adopt a code, communities often struggle with assessing the costs and benefits of the updated code in relation to their existing regulations. To assist such an evaluation, in its next steps, the project team will calculate the BCR associated with the adoption of the 2015 building code.

Existing buildings represent the vast majority of the building stock in the United States. While codes are generally applicable to new construction and to major renovations, some mitigation measures might be cost-effective for existing buildings that are not otherwise part of a major renovation. The project team will research the BCRs for various measures that can improve the resilience of existing buildings to the identified perils.

Non-building infrastructure, such as water-supply systems, are essential to the functioning of any community. As with buildings, mitigation measures can be applied to individual pieces of such infrastructure to minimize the potential damage caused by natural hazards. Over the coming months, the project team will examine water and energy infrastructure, and, to some extent, transportation and communications systems as well.

Benefits Accrue Across a Spectrum of Design Options

The selected options to exceed I-Code requirements for flood, wind, and earthquake offer a range of design levels. The project team analyzed these ranges, which include different elevations above base flood elevation (BFE), different IBHS FORTIFIED Home Hurricane design levels (Silver, Bronze, and Gold), and different strength and stiffness factor I_e for seismic design. The project team identified the point on a geographic and mathematical basis where the last incremental improvement in the design cost-effectively captures the last incremental benefit, here called the incrementally efficient maximum or IEMax. In all cases, significant benefits can be achieved cost-effectively at various levels of design up to this identified point, meaning that one can enjoy cost-effective improvement without designing all the way up to the IEMax. The ideal level of mitigation for a specific project will vary. The benefits and costs of mitigation measures at the project level should be evaluated based on the specific characteristics of the project and the needs of the owner and users. This study does not address project-level conditions or the decision-making required at an individual project level.

Table 4 provides BCRs at the state level that correspond to a range of elevations above BFE. Figures 9 and 10 illustrate the two the IBHS FORTIFIED Home Hurricane and High Wind programs, and the range of strength and stiffness factors in earthquake-prone areas that result in cost-effective design.

State	First Floor Height above BFE up to IEMax	BCR
Texas	+2 to 8	**20.2** to **9.1**
Louisiana	+2 to 10	**11.3** to **4.8**
Mississippi	+2 to 10	**27.6** to **10.1**
Alabama	+2 to 10	**31.1** to **11.7**
Florida	+2 to 10	**21.1** to **8.4**
Georgia	+2 to 6	**6.7** to **3.8**
South Carolina	+2 to 10	**11.8** to **5.0**
North Carolina	+2 to 10	**12.6** to **5.2**
Virginia	+2 to 6	**6.7** to **3.8**
Delaware	+2 to 6	**6.7** to **3.8**
Maryland	+2 to 6	**6.7** to **3.8**
New Jersey	+2 to 6	**6.7** to **3.8**
New York	+2 to 6	**6.7** to **3.8**
Connecticut	+2 to 6	**6.7** to **3.8**
Rhode Island	+2 to 6	**6.7** to **3.8**
Massachusetts	+2 to 6	**6.9** to **3.9**
Total		**16.9** to **7**

Table 4. BCRs for various heights above BFE for new coastal V-zone buildings.

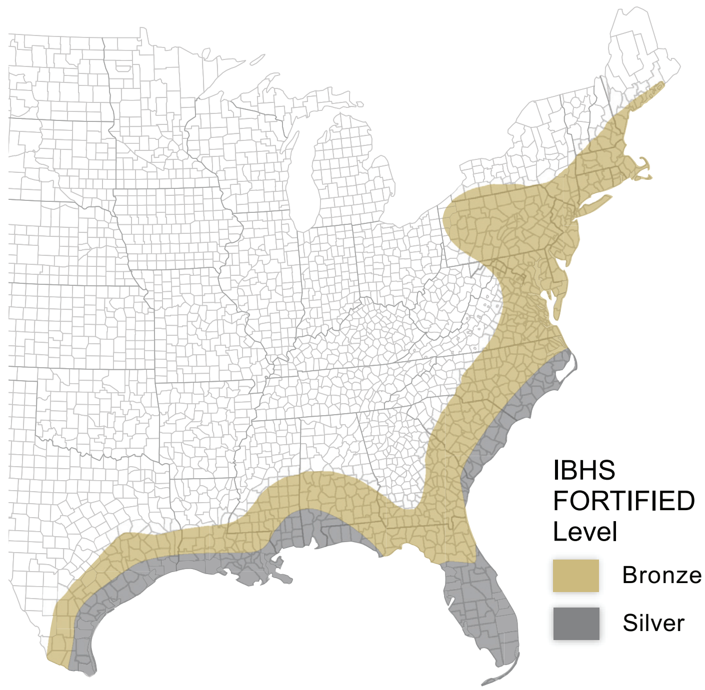

Figure 9. Maximum level of the IBHS FORTIFIED Home Hurricane design for new construction where the incremental benefit remains cost-effective.

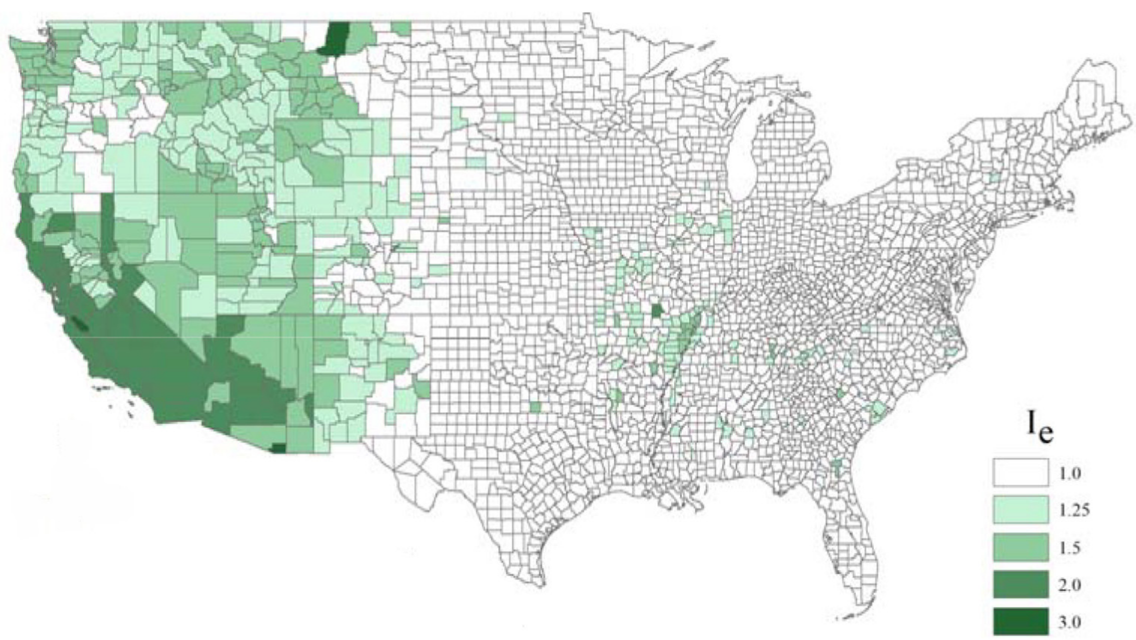

Figure 10. Maximum strength and stiffness factor I_e to exceed 2015 IBC and IRC seismic design requirements where the incremental benefit remains cost-effective.

Utilizing the Best Available Science

To provide meaningful results within a reasonable timeframe and budget, the project team identified and used the best available, yet practical, science. For example, to estimate how earthquakes damage buildings, the project team used a 20-year-old method of structural analysis. Despite the existence of newer tools, this older approach was the only practical way to account for the enormous variety of building types, heights, occupancy classes, and design requirements that have to be considered.

Focusing on single mitigation strategies provides a means for understanding mitigation options, but does not capture the nuances of individual buildings and the hazards they may face. The *Interim Report* examines the overall average cost-effectiveness of mitigating broad classes of buildings, but does not address unique features of individual buildings. The details of a particular building can make a big difference in the cost-effectiveness of mitigation. Elevating buildings reduces the chance that they will be flooded; however, people can still be stranded in elevated buildings. Designing new buildings to be stronger and stiffer in resisting earthquake loads reduces structural damage but can increase the damage to acceleration-sensitive components such as furniture and other contents, unless one also takes care to properly install or secure those components, such as by strapping tall furniture to the building frame. Furthermore, using a simple factor for greater strength and stiffness may cost more or save less than a design that uses base isolation or another design technique. Each approach has its advantages and disadvantages.

Mitigation decisions take place in contexts that involve more than tangible costs and benefits. Other decision-maker preferences; available financial resources; legal and time constraints; justice and equity; and other variables also matter. The project team did not examine these other considerations, which could matter more than BCR. Furthermore, this study offers BCR estimates as one consideration for a wide variety of possibly complex decision situations that community leaders often face.

Incentivization Can Facilitate Ideal Levels of Investment

Not everyone is willing or able to bear the up-front construction costs for more resilient buildings, even if the long-term benefits exceed the up-front costs. Different stakeholders enjoy different parts of the costs and benefits, and the people who bear more of the costs may argue more urgently against mitigation than the people who enjoy more of the benefits. However, one set of stakeholders may be able to offer incentives to others to decrease the cost or increase the benefit, and better align the competing interests of different groups. The MMC and the Institute's Council on Finance, Insurance and Real Estate (CFIRE) have proposed a holistic approach to incentives that can drive coordinated mitigation investments, aligning the interests of multiple stakeholder groups so that they all benefit from a cooperative approach to natural hazard mitigation.[6]

[6]National Institute of Building Sciences, *Developing Pre-Disaster Resilience Based on Public and Private Incentivization* (2015). http://www.nibs.org/resource/resmgr/MMC/MMC_ResilienceIncentivesWP.pdf

Results Inform Mitigation Decision Making

This *Summary of Findings* and the ongoing study add to the growing body of scientific evidence that demonstrates that mitigation lessens the financial impact of disasters on local businesses, communities, and taxpayers and it thus enables individuals and communities to recover more rapidly from these events when they do occur. Additionally, it affirms that decision-makers, including governments, building owners, developers, tenants, and others, should consider opportunities for implementing mitigation activities to reduce the threat to lives, homes, businesses, schools, and communities, while also reducing future repair and rebuilding costs.

Expert Contributions to This Study

The Institute project team, which consisted of eight authors and two leaders, developed the methodology with oversight by a committee of 15 independent experts, who peer-reviewed the work and confirmed the results. Institute staff directed and managed the overall effort. FEMA provided additional review by 20 subject matter experts. Other agencies of the federal government, including EDA within the U.S. Department of Commerce, HUD, and the Office of Management and Budget also contributed nine experts who provided input in developing the project, its methods, data, and products, or reviewed the study for reasonableness and usefulness. In particular, HUD, along with FEMA, provided economic input to the benefit-cost methodology. A total of 43 other representatives from 32 other organizations and stakeholder groups, including banking, insurance, government, construction, natural hazards, economic policy, environmental science, and structural engineering, provided oversight and peer review. The project team is well-known for expertise in earthquake engineering, fire, flood, and wind risk, as well as engineering economics and disaster sociology. Several of the authors participated in or helped lead the 2005 study. In total, the Interim Study represents the combined effort of 97 experts in virtually all fields relevant to natural hazard mitigation in the United States.

Federal- and Private-Sector Support for the 2017 Study

A number of public- and private-sector organizations interested in expanding the understanding of the benefits of hazard mitigation generously funded the research presented in this *Interim Report,* as well as the project team's ongoing work. Funders to date are Premier Plus Sponsor FEMA; Premier Sponsors EDA and HUD; Lead Sponsor International Code Council; Sponsors IBHS and National Fire Protection Agency; and Supporter American Institute of Architects. While representatives from these organizations provided data and expertise to the project team, their input was largely informative, resulting in a truly independent study. The Institute seeks additional funders to support the study of additional mitigation measures.

Natural Hazard Mitigation Saves: 2017 Interim Report

Technical Documentation

1 Introduction

1.1 Background

Hurricanes, tornadoes, floods, earthquakes, and wildfires are inevitable. Because of a variety of factors, the impacts of these events are expected to increase—particularly during the useful life of much existing and most new U.S. infrastructure. These environmental stresses will damage property, injure, and kill people, threaten the viability of entire communities, and severely impact the U.S. economy. Increased density and complexity of the urban environment also increase the likelihood of larger, more costly disasters. Society will certainly bear the costs to respond to such events.

Fortunately, there are measures governments, building owners, developers, tenants, and others can take to reduce the impacts of hazard events. These measures—called mitigation—can result in significant savings in terms of safety, and prevention of property loss, and disruption of day-to-day life. Data should inform decision-making around the level and timing of mitigation investments. Important data include the increase in safety, decreased economic impact and human misery, jobs saved or created, and the speed of business activity recovery associated with a particular level of investment.

The National Institute of Building Sciences (Institute), through its Multihazard Mitigation Council (MMC), works to advance the utilization of cost-effective solutions to reduce the impacts of hazards. In 2005, the Institute published the results of a study that examined the benefits of investments by the Federal Emergency Management Agency (FEMA) in disaster mitigation (MMC 2005). The results presented in this Interim Study, an update and expansion of the 2005 study, attempt to answer questions that inform mitigation and present the first broad set of hazards and mitigation measures. The project team will evaluate additional mitigation measures and provide BCRs on such measures once available.

The *Summary of Findings* is accessible to the general public and policymakers, while the *Technical Documentation* presents a detailed technical analysis of these questions. The *Technical Documentation* speaks specifically to specialists: scientists, engineers, architects, and social scientists who want to understand the Interim Study's objectives, mathematical methods, and findings in great detail. Appendix M provides a series of stand-alone documents that will be useful in communicating Interim Study results to a widespread audience of policymakers, businesspeople, and homeowners who make decisions on how to implement natural hazard mitigation strategies.

Both volumes seek to provide insight to those who will make hazard-mitigation investments based on the benefit-cost ratio (BCR) of their investment by answering the following questions:

- What is the overall average BCR for U.S. natural hazard mitigation efforts?
- Under what conditions—what locations, what hazards, what particular mitigation measures, what categories of infrastructure—is the BCR higher or lower?
- Can one identify mitigation efforts not yet undertaken that would have a higher BCR, and use that information to make better investments in public and private infrastructure?

Answers to these questions can inform a variety of mitigation decisions, but they do not touch on many of the relevant variables. Mitigation decisions take place in business, political, social, and personal contexts that involve benefits and costs, but also preferences, financial resources, legal and time constraints, justice and equity, and other variables that far exceed the scope of this Interim Study. The Interim Study only considers the benefits and costs of some leading mitigation options. It does not identify or examine the local context under which mitigation decisions are made. Local, regional, and even statewide factors may influence mitigation decisions. The project team therefore makes no recommendations nor does it advocate for one mitigation option over another, or advocate for mitigation over not mitigating. The Interim Study offers benefit and cost information merely to serve as a resource in making complex mitigation decisions.

People commonly measure benefits and costs with BCRs. Other metrics besides BCR can quantify the desirability of mitigation, including the degree to which mitigation reduces total cost of ownership. Mitigation can reduce the probability of catastrophic outcomes. A business decision-maker thinking about how mitigation affects profits might use BCR to decide whether an investment is worthwhile. On the other hand, if the decision-maker thinks that a natural hazard might threaten the survival of the business, a BCR is the wrong measure to use. The decision-maker should consider losses in a rare event, e.g., such as a low-probability event with major impacts, through loss-exceedance curves or, more qualitatively, by considering outcomes in a few disaster scenarios. This Interim Study does not quantify loss-exceedance curves.

This Interim Study evaluates BCRs in large part because U.S. infrastructure investments must be "based on systematic analysis of expected benefits and costs, including both quantitative and qualitative measures" (Clinton 1994). BCR is straightforward and a commonly used metric of expected benefits and costs. The 2005 *Mitigation Saves* study measured the efficacy of natural hazard mitigation in terms of BCR.

The 2005 Study resulted from a 1999 request by the U.S. Congress instructing FEMA to conduct an independent review of the benefits and costs of FEMA-funded natural hazard mitigation efforts. That study found, among other things that on average, FEMA-funded natural hazard mitigation saved $4 for every $1 spent.[1] The 4:1 study has subsequently been cited hundreds of times in scholarly literature, dozens of times in Congressional hearings, and many times in

[1] The ratio was shown to vary between perils and other factors, but people tend most often to quote the overall number.

Box 1-1. Mitigation Measures to be Examined in 2017/2018 *Mitigation Saves* Study

- Code adoption and designing to exceed International Code (I-Code) requirements. What benefit can be provided by designing new buildings to exceed the requirements of the *2015 International Building Code* (IBC) and *2015 International Residential Code* (IRC) for flood, wind, and earthquake resistance? What benefit can be provided by adopting the *2015 International Wildland-Urban Interface Code* (IWUIC)? (70% complete)
- About one in three communities has not adopted the I-Codes, or has weakened their disaster-resistance requirements. What benefit is provided by adopting the 2015 IBC and 2015 IRC for flood, wind, and earthquake resistance? (Funded for 2018)
- Private-sector retrofit of existing facilities. FEMA guidelines and other common practices remediate deficiencies of existing facilities' resistance to various natural hazards. What are some leading options and how cost-effective are they? (60% funded for 2018)
- Business continuity planning (BCP) and disaster recovery (DR). How cost-effective is BCP/DR in the private sector? (Future)
- Utility and transportation lifeline mitigation. What are some leading options to make utilities and transportation lifelines more disaster-resistant, and how cost-effective are they? (50% funded for 2018)
- Public-sector grants to support mitigation. Since 1993, how cost-effective were natural hazard mitigation efforts undertaken with funding support from various federal agencies? (Complete)
- Public-sector direct mitigation efforts. How cost-effective have been various direct mitigation actions by federal agencies? Many government agencies engage in natural hazard mitigation as part of their mission, such as the U.S. Army Corps of Engineers (USACE) flood-control efforts, the National Weather Service (NWS) work on hurricane forecasting, and the U.S. Geological Survey (USGS) efforts to develop earthquake early warning systems. (Future)

reports, public presentations, and elsewhere, as information to inform and support increased investment in natural hazard mitigation.

As useful as the 4:1 ratio has proven to be in communicating the BCR of mitigation, FEMA-funded mitigation represents only a fraction of all natural-hazard mitigation in the United States. Intuitively, building a new facility to be more disaster-resistant is likely to cost less than retrofitting that facility to the same level of disaster resistance after the fact. The 4:1 ratio may underestimate the benefit of other classes of natural hazard mitigation. Current building codes have already substantially advanced safety and property protection relative to prior codes.

The 2005 study focused solely on FEMA-funded mitigation activities. However, other federal agencies also perform or fund mitigation activities, such as the Economic Development Administration (EDA) and U.S. Department of Housing and Urban Development (HUD).

1.2 Objectives

The *2017 Interim Report* updates and expands upon the mitigation measures studied in 2005 by evaluating a broad suite of mitigation measures that can inform decision-making around investments to reduce the impacts of natural hazards. This *Interim Report* focuses on the results from two specific strategies: the benefits and costs of new buildings designed to exceed select model building code requirements provided by the International Code Council (ICC) and the cost-effectiveness of grants by federal agencies. Box 1-1 summarizes the natural hazard mitigation topics identified for study, those covered to date, and those funded for study. See Section 1.3 for additional details on these Interim Study topics. Ongoing research will examine additional mitigation measures that will be incorporated into future reports.

The project team studied two categories of natural hazard mitigation efforts to date:

1. **Design of ordinary new buildings to exceed current requirements of the unamended 2015 IBC and IRC, and to conform to the 2015 IWUIC** (ICC 2015a, b, c). Model codes represent minimum requirements, not maxima. What might be the costs and benefits of exceeding those minima? This Interim Study addresses that question by estimating the costs and benefits of exceeding code minima in a few particular ways. This is not to say there is anything wrong with current codes, which offer great improvements in performance relative to older codes. I-Codes aim largely, though not exclusively, to protect immediate life safety. For example, the intent of the 2015 National Earthquake Hazards Reduction Program (NEHRP) *Recommended Seismic Provisions* (FEMA 2015d), which underpins the I-Code seismic requirements, is "to provide reasonable assurance of seismic performance that will avoid serious injury and life loss … preserve means of egress, avoid loss of function in critical facilities, and reduce structural and nonstructural repair costs where practicable." Its provisions allow for substantial damage at the levels of shaking that approach the risk-targeted maximum earthquake considered in the codes and underlying standards. Recent earthquakes have shown that buildings in the epicentral region can experience such high levels of shaking.

   As leaders wish to address the resilience of their communities, the long-term, ongoing safety and operations of buildings requires consideration of measures that enhance current code minimums.

   This Interim Study addresses whether it is economical to exceed life safety by reducing damage and perhaps increasing the likelihood of immediate occupancy of buildings after a natural disaster. This Interim Study examines the risk-category II buildings of the 2015 IBC: the homes, strip malls, office complexes, industrial buildings, and so on that comprise the vast majority of new buildings. This *Interim Report* does not address the less-common (though still important) buildings of risk categories I (e.g., minor storage facilities), III (e.g., auditoriums) or IV (e.g., hospitals).

   While not covered in this Interim Study, it is equally important to understand the BCR of having a current building code in place versus an older code, or even no code at all. As of June 2017, about one-third of communities in hazard-prone areas have not adopted a recent version of the I-Codes (either the 2009, 2012, or 2015 edition) without weakening the disaster-resilience features. As a later part of the study, the project team will evaluate the BCR of code adoption.

2. **Mitigation of existing buildings funded by FEMA, EDA, and HUD**. The federal agency strategies consider 23 years of public-sector mitigation of buildings funded through FEMA programs, including the Flood Mitigation Assistance Grant Program (FMA), Hazard Mitigation Grant Program (HMGP), Public Assistance Program (PA), and Pre-Disaster Mitigation Grant Program (PDM), as well as the HUD Community Development Block Grant Program (CDBG) and several programs of the EDA. Barring identification of additional federal data sets or sources of federal mitigation grant and loan funding, these analyses represent essentially a comprehensive picture of such mitigation measures. Mitigation efforts within other federal agencies including the U.S. Department of Transportation (DOT) and within agencies where measures are implemented directly (e.g., U.S. Army Corps of Engineers (USACE) flood control) may be the subject of future study. Some of the mitigation work funded by grants from these agencies may have used criteria from the IBC and IRC, but also the *International Existing Building Code* (IEBC) and additional criteria such as that identified in Chapter 2.[2] (2015d and earlier editions).

This Interim Study does not address all categories of natural hazard mitigation, so inferences about the cost-effectiveness of those other categories should not be made. For example, the study does not addresses exceeding code requirements either to resist tornadic winds or to further elevate structures in Coastal A zones.. As it continues its work, the project team will address many of these categories of natural hazard mitigation, as discussed in the next section.

The project team estimated the benefits of natural hazard mitigation in terms of avoided future losses. The team considered reductions in all major loss categories: property repairs, casualties, and direct and indirect business interruption (BI). Several benefit categories could not be readily quantified in dollar terms, so the project team acknowledged them qualitatively. (See Box 1-2 for benefit categories, both tangible and intangible.) Not every benefit category in this list can be quantified, and some of the remainder are notoriously difficult to estimate. The project team also distinguished BCRs by peril, focusing on four of the most common and damaging sudden-onset hazards that damage property and hurt people across the United States: flood, wind, earthquake, and fire at the wildland-urban interface (WUI). These are the same perils examined in the 2005 *Mitigation Saves* study, with the addition of fire at the WUI. As in the 2005 *Mitigation Saves* study, the present Interim Study limits its estimates of avoided future losses mostly to the owners and tenants of mitigated buildings, and ignores the fact that when those people lose money, for example, to pay for repairs, the money gets transferred to somebody else, such as construction contractors.

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[2] The IEBC establishes target performance levels for existing buildings and ensures a more consistent degree of performance.

Box 1-2. Benefit Categories Considered

1. Reduced future property repair and reconstruction costs.
2. Reduced additional living expenses (ALE) and other costs of residential displacement.
3. Reduced future losses associated with direct BI, meaning the loss of revenue resulting from damage at the facility in question that prevents it from being used for production.
4. Reduced future losses associated with indirect BI, meaning the loss of revenue resulting from damage at other facilities.
5. Lower insurance costs.
6. Reduced costs for emergency response.
7. Reduced loss of service to the community, especially for fire stations and hospitals.
8. Lower maintenance costs.
9. Improved public-health outcomes, especially deaths, nonfatal injuries, and post-traumatic stress disorder (PTSD). Public health outcomes are expressed in terms of incidents and are then monetized using the acceptable cost to avoid future statistical deaths and injuries. Note that one can estimate the acceptable costs to avoid mental-health impacts (not addressed in the 2005 study), which Bloom et al. (2011) suggest is a dominant contributor to the global economic burden of non-communicable diseases.
10. Fewer job losses and some job creation.
11. Lower environmental impacts.
12. Reduced historical and other cultural impacts.
13. Impact on tax revenues.

The project team examined design objectives for new buildings from the perspective of an owner or developer choosing between meeting versus exceeding the 2015 I-Codes, or in the case of the 2015 IWUIC, simply adopting it. The project team used the 2015 editions as the baseline to examine the costs and benefits of exceeding code requirements for new design. Where a community has adopted an earlier version of the code or no code, the BCR will change.

A few owners have chosen to exceed code minima, such as the California Institute of Technology (CalTech), which for several decades constructed its buildings to be 50% stronger than the code required. At least two consulting clients of project team members currently design some of their new buildings to be 25% stronger than the code requires. A local jurisdiction could make the same choice for portions of its community. Its decision-makers would benefit from knowing: (1) the reasonable options; (2) the costs and benefits of such options; and (3) who would bear or enjoy the costs and benefits. Costs include the up-front expenses required to enjoy the possible benefits. Up-front expenses might include higher costs of design, construction, enforcement and maintenance. Stakeholders would realize different benefits; building owners would benefit from reduced building repair costs, tenants would benefit from reduced content repair costs, and the broader community would benefit from reduced indirect BI losses.

Results might vary by peril, geographic location, socioeconomic status, and economic sector. The project addresses these questions by imagining a future building stock composed entirely of buildings that comply with the current I-Codes (especially the 2015 IBC, IRC, and IWUIC), and then again a different future building stock composed of buildings designed to exceed I-Code requirements, such as with greater strength, stiffness, height above base flood elevation (BFE), etc. In the case of the 2015 IWUIC, the project addresses the questions by imagining that new buildings do not comply with that code, and then again supposing that new buildings do comply. The Interim Study identifies locations where designing to exceed I-Code requirements appears to be cost-effective, and estimates the degree to which designing to exceed I-Code requirements in those locations makes economic sense on a BCR basis. Box 1-3 explains how the project team's approach to consider only measures that appear cost effective do not produce bias.

For designing to exceed the 2015 I-Codes (or designing to comply with the 2015 IWUIC), the project team estimated the costs and benefits for 1 year of new buildings, e.g., assuming that all new buildings built in 2018 are built to comply with the stricter requirements, but only where it is cost-effective to do so.

Box 1-3. A Note on Bias and Measuring Cost Effectiveness

Some critics may perceive that calculating the BCR for designing to exceed I-Code requirements where it is cost-effective to do so somehow produces biased results, or an implicit kind of advocacy. The 2005 Mitigation Saves study aimed to produce an independent estimate of the BCR for FEMA-funded natural hazard mitigation undertaken between 1993 and 2003. For the most part, FEMA only funded mitigation efforts in which proponents were able to estimate that the BCR exceeded 1.0. The 2017 project team continued this Interim Study with the same objective. Estimating the average BCR of implementing above-code design should only consider such an approach where cost effective (i.e., BCR is greater than 1.0). This gives readers a sense of how cost-effective natural hazard mitigation can be, in cases where it is cost-effective at all. The Interim Study attempts to show or describe the locations where designing to exceed I-Code requirements saves more than it costs, on a long-term, average basis, cost-effectively and where it does not. (With little if any accidental bias. Where some quantity is highly uncertain and strongly affects BCR, the project team attempts to err on the conservative side, e.g., to under-estimate BCR rather than over-estimate it.)

The Interim Study examines federal mitigation grants from the perspectives of the funder, grant recipient, tenants, and the community near the mitigation activity. The Interim Study does not consider the adoption of the whole codes studied, but instead estimates the costs and benefits of narrowly defined changes. For example, what if a California city considering adoption of the 2015 IBC also considered requiring that all new buildings must comply with the seismic strength, stiffness, and equipment anchorage requirements for risk-category IV buildings? That would make most new buildings at least 50% stronger and stiffer than they otherwise would be. Such a narrowly defined enhancement would not involve other requirements, such as changes in wind resistance that might be stated elsewhere in the code. The project team estimated the costs and benefits associated with just the one enhancement, ignoring how the enhancement for seismic resistance might affect wind resistance.

A number of different stakeholders might potentially be interested in the results of this Interim Study. Box 1-4 identifies categories of stakeholders and intended audiences for the *Summary of Findings* and the *Technical Documentation*.

The project team aimed first to produce this Interim Study, documenting its methodologies and findings. The project team set out to assure quality through a rigorous peer review process, in which each section was reviewed by at least two highly qualified experts working independently of the project team. This Interim Study represents an "independent inquiry," meaning the authors are independent of the funding organizations for this Interim Study.

1.3 Future *Mitigation Saves* Study Activities

This Interim Study presents analysis to determine the benefits and costs of pre-disaster mitigation strategies for new private-sector construction and grants to mitigate existing public-sector buildings. This analysis began in October 2016 and concluded in October 2017.

Beginning in late 2017, the project team will continue its research, assessing the cost-effectiveness of bringing states with significant flood, wind, and earthquake hazards and inadequate or no disaster-resistant codes up to the level of resistance afforded by the 2015 IBC and the 2015 IRC. A disaster-resistant code is defined here as the 2009 and later editions of the IBC and IRC.

Box 1-4. Stakeholder Categories and Intended Audience

Insurers:	Primary and reinsurance companies, state insurance authorities
Finance:	Mortgage companies, appraisers and real estate brokers Loan organizations: Property Assessed Clean Energy (PACE), tax increment financing, American public-private partnership (P3) model,, Community Development Financial Institution (CDFI), green banks, cat bond issuers, real estate investment trusts (REITs), bond rating agencies
Designers:	Architects, land use planners, structural and civil engineers and their professional societies
Builders:	Developers, builders, contractors, and their trade associations
Public sector:	Mayors, county supervisors, city and county council members, building officials, community development agencies, fire departments, emergency responders and managers, state legislatures, other state agencies: utility commissions, state architects, state departments of transportation, housing, school boards, U.S. Congress and federal agencies: FEMA, HUD, Small Business Administration (SBA), EDA, DOT, Fannie Mae, Federal Housing Administration (FHA), Freddie Mac, Department of Veterans Affairs (VA), Department of Energy (DOE), Department of Agriculture (USDA)
Private sector:	Homeowners, large businesses, small businesses and utilities
Outreach:	Media, universities, hazard-related organizations, building-related organizations

The project team also will estimate the cost-effectiveness of retrofits of existing private-sector buildings to enhance their resilience to natural disasters. The project team will consider mitigation efforts to reduce risk from flood, wind, earthquake, and fire at the WUI that meet at least two of three criteria:

- Commonly implemented, but probably cost-effective.
- Conducive to reducing uninsured losses.
- Of particular interest to the National Fire Protection Association (NFPA) and HUD, because the retrofit solves a deficiency in many HUD-funded buildings, the retrofit is affordable to HUD occupants, or HUD provides funding for the retrofit measure.

Mitigation strategies for potential study are identified and prioritized in Table 1-1. In its ongoing research, the project team will examine all priority-1 measures, at least one priority-2 measure for each peril, and, possibly, priority-3 perils if it is found that the priority-1 and priority-2 measures can be evaluated without exhausting the available time and budget. Input from sponsors, oversight committee members, and stakeholders will determine which priority-3 measures can be examined.

Peril	Mitigation Measure	Priority
Flood	Elevation	1
	Buyout	1
	Wet flood proofing	2
	Dry flood proofing	3
	Land use planning	3
	Site perimeter flood proofing	3
Wind	Manufactured housing engineered tie-down system (ETS)	1
	IBHS FORTIFIED Home (existing home, hurricane)	2
	IBHS FORTIFIED Home (existing home, high wind)	3
	Stronger vents, soffits, and overhangs at gable end walls	3
	Stronger connections of attached structures	3
Earthquake	Furnishings, fixtures, and equipment restraints	1
	Manufactured housing engineered tie-down system (ETS)	1
	Foundation anchors & strengthen cripple walls to older wood buildings	2
	Seismic gas shutoff valves	2
	Stronger unreinforced masonry bearing-wall (UMB) buildings	3
	Stronger roof-to-wall connections in older tiltup and reinforced masonry	3
	Steel frames or wood shearwalls to soft-story multi-family dwellings	3
WUI	Retrofit to approach 2015 IWUI Code	1

Table 1-1. Retrofit measures to be examined in the ongoing study.

A third analysis will examine the cost-effectiveness of natural hazard mitigation to reduce risk for utilities and transportation lifelines projects funded by the EDA and in the public or private sectors. This line of inquiry will likely analyze the mitigation of flood risk for most or all of: electricity, telecommunication, ports, rail, and roads, as well as the mitigation of wind risk to electricity and telecommunications. The ongoing study will examine:

- A leading lifeline mitigation effort for fire at the WUI: controlled burns to reduce drinking-water reservoir turbidity caused by soil in runoff.
- A leading measure to increase the resilience of telecommunication and electric systems to earthquake: strengthening of equipment at substations and telecommunication central offices.
- A promising earthquake mitigation measure for water, wastewater, and sewer, called a resilient grid.

The Institute will release data on additional mitigation measures as they become available. Additional future work, pending identification of funding resources, will examine BCP and DR, as well as mitigation activities performed by federal agencies, such as the National Oceanic and Atmospheric Administration (NOAA) early warning system and the USACE levee programs.

1.4 Organization of Interim Report

This chapter introduces the project team's objectives and some of the important considerations in quantifying the costs and benefits of mitigation. Chapter 2 summarizes the findings. Chapter 3 briefly recaps past efforts to perform similar or related studies. Chapter 4 presents the methods selected to meet the Interim Study objectives. Chapter 5 summarizes the data acquired. Chapter 6 lists the references cited elsewhere in the Interim Study. Miscellaneous additional documentation such as a glossary and a set of brief summaries of particular mitigation measures or categories of measures, with the aim of informing decisions by a particular stakeholder group appears in the appendices.

2 Findings

2.1 Summary Results

Based on the mitigation measures examined for this *Interim Report*, mitigation remains a solid investment. Implementing mitigation measures in new construction to exceed select provisions in the 2015 IBC and the 2015 IRC and the implementation of the IWUIC saves society $4 for every $1 spent, resulting in a national BCR of 4:1. Federal mitigation grants provided by FEMA, EDA, and HUD result in $6 of benefit for every $1 spent, producing a national BCR of 6:1. As the project team studies additional mitigation measures, this report will expand to incorporate new findings. Eventually, once the project team has identified BCRs for a suite of mitigation measures, they will aggregate them into a BCR that reflects the overall value of implementing mitigation. (See Box 1-1 for a discussion of why such an aggregation is not provided at this time.)

The national-level BCRs aggregate the study findings across natural hazards and across state and local BCRs. The Interim Study examined four specific natural hazards: riverine and coastal flooding, hurricanes, earthquakes, and fires at the WUI. Table 2-1 summarizes the BCRs for each set of mitigation measures and the individual natural hazards the project team examined. The sections that follow provide an in-depth discussion of the results and key considerations in determining mitigation measure- and hazard-specific BCRs.

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	6:1	4:1
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 2-1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

Box 2-1. Why Two BCRs?

This *Interim Report* of results features two high-level BCRs representing the benefits of mitigation achievable by exceeding code provisions and through federal grant programs. While the project team recognizes the desire to have a single BCR that would facilitate widespread dissemination of the project results, providing such an aggregate number will be more useful when other parts of the *Mitigation Saves* study are completed.

The 2005 study produced the widely cited results that showed a $4 benefit for every $1 invested in mitigation. Despite the specific guidance that the result represented only a single, very narrow set of mitigation strategies, specifically those funded through FEMA mitigation grants, the BCR has been used to justify all types of mitigation strategies. The *2017 Interim Report* provides an updated examination of the benefits of federal agency grant programs (including the addition of EDA and HUD), resulting in a $6 benefit for every $1 invested. While not a direct replacement, when used to describe federal grant programs, the 6:1 BCR can be used in place of the original 4:1.

The *2017 Interim Report* also includes the results from the examination of a new set of mitigation measures: exceeding the 2015 IBC and IRC and implementing the 2015 IWUIC. These strategies provide an aggregate benefit of 4:1. While these mitigation measures are an important addition to the dialogue around mitigation, they still only represent a few of many practical strategies.

In lieu of providing a result based on a limited set of mitigation measures, with the result likely to change as new mitigation strategies are studied and added to the aggregate number, the project team elected to provide BCRs for each strategy individually. Once the project team has identified BCRs for a sufficient number of mitigation strategies, it will provide an aggregated number representing the overall benefit of mitigation.

2.2 Results From Designing to Exceed 2015 I-Code Requirements

The section presents benefit-cost analysis (BCA) results of designing new buildings to exceed 2015 IBC requirements (in the case of riverine flood, hurricane storm surge in coastal V-zones, wind, and earthquake) or to comply with the requirements of the 2015 IWUIC (in the case of wildfire).

2.2.1 Designing to Exceed 2015 I-Code Requirements for Riverine Flood

The cost to build all new homes to the BFE + 5 feet for 1 year is approximately $900 million. This would produce approximately $4.2 billion in benefits, for an aggregate BCR of approximately 5:1, e.g., $5 saved for every $1 spent to build new homes higher out of the floodplain.

If all new residences in the United States in the 1% annual chance floodplain were designed to BFE + 5 and achieved the overall average BCR of 4.67 shown in Figure 2-2, what would be the total societal costs and benefits for 1 year of new construction? There are approximately 5.1 million National Flood Insurance Program (NFIP) policies currently in force in the United

States.[3] NFIP's market penetration (ratio of houses that are insured to the total number that could be insured) is approximately 0.5.[4] Together, these two statistics suggest approximately 10.2 million U.S. homes are currently in the 1% annual chance floodplain. On average, construction adds about 1% to the existing building stock, which suggests that 102,000 houses will be built in one average year in the 1% annual chance floodplain (1% of 10.2 million = 102,000). The additional cost to build to BFE + 5 rather than BFE + 1 is approximately $8,900 for a single house, or about $900 million for 102,000 new houses. With a BCR of 4.67, the benefits would total about $4.2 billion ($900 million x 4.67). The benefit comes from reduction in property losses, additional living expenses (ALE), sheltering, and indirect BI, casualties and PTSD, and insurance, in the proportions shown in Figure 2-1.

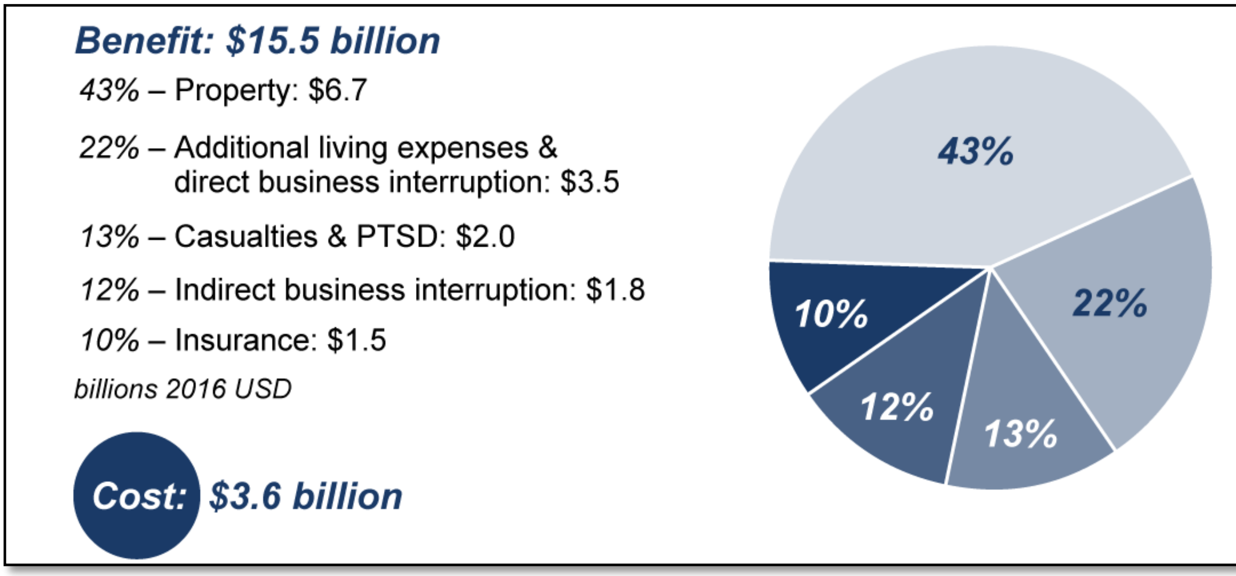

Figure 2-1. Nationwide benefits by category for designing to exceed 2015 I-Code requirements for flood.

In Figure 2-1, the label "additional living expenses and sheltering" means the cost to residents or to the rest of society resulting from the loss of use of residential property—the analog of direct BI in residential property. Indirect BI refers to the net reduction in economic activity resulting from the loss of use of the residential property, aside from the ALE. The same is true of several other pie charts in this chapter. In some cases, the living expenses and indirect BI are combined in a pie chart, or direct and indirect BI. Where practical, they are separated. Figure 2-1 adds smaller benefits and costs associated with hurricane surge, discussed in Section 2.1.2.

This Interim Study estimates the nationwide effectiveness of designing and building all new homes in 1 year in the 1% annual chance floodplain to exceed 2015 I-Code requirements. It does not purport to present a precise estimate of benefits that might be realized on a case-by-case local basis (e.g., census tracts), or if such precise calculations were carried out on a local basis in every floodplain across the entire nation and then summed. Local results for a particular house or for

[3] https://www.fema.gov/total-policies-force-calendar-year

[4] https://www.fema.gov/media-library-data/20130726-1602-20490-2804/nfip_eval_market_penetration_rate.pdf, pg. xiii

all the houses in a particular community would probably differ from the average presented here. The true nationwide benefits and costs, if they could be calculated for every county in the United States, would also differ by some unknown amount from the estimates this report provides. However, more often than not there would probably be a benefit to mitigating.

The project team used a purposive sampling technique of typical cases of communities that represent common floodplain conditions and residential structures found in riverine flooding across the United States, as described in Section 4.8.2. Table 2-2 summarizes the statistics for the four counties studied. Results are reported for each foot of increase in elevation at a 2.2% discount rate (the approximate cost of borrowing) and an assumed 75-year economic life of a residence. (See Appendices H and I for a discussion of the discount rate and of the economic life of a building, respectively.) The table shows the benefits and costs for additional elevation above code-minimum: BFE + 2 means new design to 2 feet above BFE, for example. “Cost” refers to the total additional cost of building to the specified height rather than I-Code minimum (BFE + 1). It is the difference in construction cost between BFE + *n* feet (e.g., “BFE + 2 means 2 feet above BFE) and BFE + 1. Benefit means the present value of benefits resulting from the additional elevation. BCR refers to the ratio of the two. ΔCost refers to the difference in additional cost to build to BFE + *n* feet rather than BFE + (*n* – 1) feet, or the additional cost of one additional foot of elevation from BFE + (*n* – 1) to BFE + *n*. ΔBenefit refers to additional benefit of building to BFE + *n* rather than BFE + (*n* – 1). ΔB/ΔC refers to the ratio of ΔBenefit to ΔCost. Each additional foot of elevation is considered cost-effective if ΔB/ΔC > 1.

ΔB/ΔC is greater than 1 for all elevations considered. Table 2-2 suggests that designing buildings with increased elevation above the I-Code 2015 requirement (BFE+1 foot) is generally cost-effective, at least up to BFE + 5 feet (4 feet more than the 2015 IBC requires) in these four counties. Figure 2-2 shows results for each county separately. Figure 2-3 shows average BCR and average ΔB/ΔC values, e.g., averaging over these four counties. While Monroe County, Georgia, has higher values of BCR and ΔB/ΔC than the other three counties, all four counties show consistent results, in that all suggest greater elevation passes the BCR > 1 and ΔB/ΔC > 1 tests of cost-effectiveness.

Height	Cost	Benefit	BCR	ΔCost	ΔBenefit	ΔB/ΔC
Allen County, IN						
BFE + 2	$ 793,972	$ 3,275,548	4.13	$ 793,972	$ 3,275,548	4.13
BFE + 3	$ 1,191,106	$ 5,665,808	4.76	$ 397,134	$ 2,390,260	6.02
BFE + 4	$ 1,588,023	$ 7,614,300	4.79	$ 396,917	$ 1,948,493	4.91
BFE + 5	$ 2,022,687	$ 8,418,696	4.16	$ 434,663	$ 804,396	1.85
Elkhart County, IN						
BFE + 2	$ 2,537,343	$ 9,534,636	3.76	$2,537,343	$ 9,534,636	3.76
BFE + 3	$ 3,806,507	$ 15,925,500	4.18	$1,269,164	$ 6,390,864	5.04
BFE + 4	$ 5,074,995	$ 19,968,948	3.93	$1,268,488	$ 4,043,448	3.19
BFE + 5	$ 6,464,192	$ 22,607,799	3.50	$1,389,197	$ 2,638,850	1.90
Fulton County, GA						
BFE + 2	$ 3,516,281	$ 14,810,326	4.21	$3,516,281	$14,810,326	4.21
BFE + 3	$ 5,275,131	$ 28,508,125	5.40	$1,758,849	$13,697,800	7.79
BFE + 4	$ 7,033,070	$ 39,734,000	5.65	$1,757,940	$11,225,874	6.39
BFE + 5	$ 8,958,412	$ 48,776,327	5.44	$1,925,342	$ 9,042,327	4.70
Monroe County, GA						
BFE + 2	$ 185,855	$ 1,619,143	8.71	$ 185,855	$ 1,619,143	8.71
BFE + 3	$ 270,575	$ 2,868,257	10.60	$ 84,720	$ 1,249,113	14.74
BFE + 4	$ 359,165	$ 3,450,872	9.61	$ 88,591	$ 582,615	6.58
BFE + 5	$ 452,175	$ 3,826,023	8.46	$ 93,010	$ 375,151	4.03

Table 2-2. Summary BCR results for sampled counties.

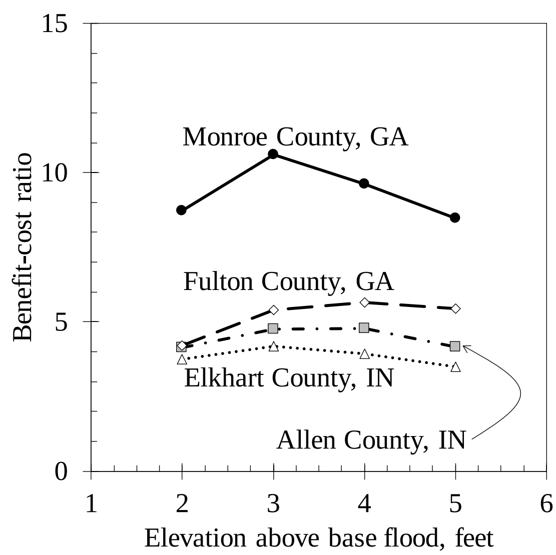

Figure 2-2. BCR by sample county and additional elevation.

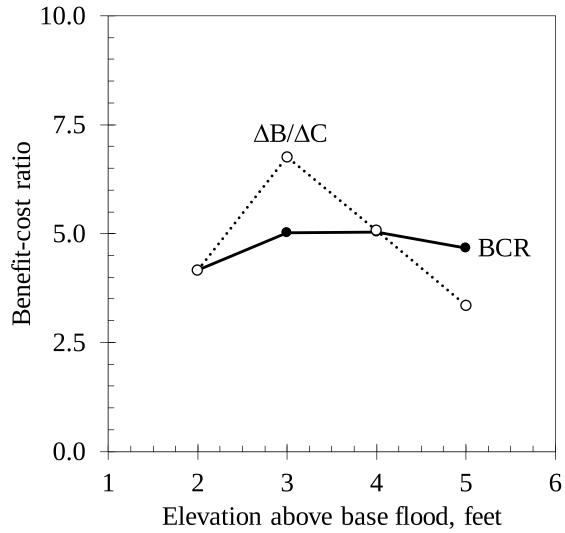

Figure 2-3. BCR and ΔB/ΔC to build new buildings higher above BFE than required by the 2015 IBC.

Some key observations are worth noting. First, there are differences between overall BCR values (a BCR at given elevation compared to BFE + 1) and ΔB/ΔC estimates. Variations among BCR values tend to be more subtle than drastic variations among ΔB/ΔC values, especially at higher elevations. That is expected: the more height above BFE, the more costs compared with the previous elevation but lesser benefit; ΔB/ΔC measures that incremental effect, while BCR adds the last-foot costs and benefits along with all the others, so the cost-effectiveness of the last foot gets concealed to some extent. It is generally cost-effective to construct a new building higher than BFE + 1, even up to 4 additional feet.

Second, BCR values seem to decline beyond a certain threshold. The project team found that with more than 4 to 5 feet of additional elevation, BCR and ΔB/ΔC diminished. This trend was consistent across all four of the sample counties and is likely to be consistent in similar communities across the nation.

Finally, it is obvious that variations among BCR values are specific to locational and community conditions (Table 2-2). This is evident by the noticeable difference in BCR values between Monroe County, Georgia, and the other three counties, and also among the other three counties themselves. Monroe County has a considerably higher percentage of open foundations than what is present in the other three counties. The BCR values for Monroe County are actually similar to those seen in the analysis of the effectiveness of elevation in coastal communities that are also dominated by open foundations, as discussed in Section 2.1.3. Although closed foundations are more common in the other counties, variations among BCR values still occur because of site-specific conditions such as level of inundation or because of socioeconomic characteristics, such as variations in construction costs or distribution of business activities within the floodplain communities.

To further investigate the latter observation, the project team tested a number of regression models using the BCR as a dependent variable. The available, relevant independent variables include elevation above BFE, foundation type, number of stories, and foundation size. One of the statistically significant models accurately predicted BCRs as a function of two independent variables: (1) elevation above BFE and (2) foundation type. This regression analysis produced an R^2 value of 0.81, which means that 81% of variance in BCR among the sampled counties in a 0.2% annual chance floodplain can be explained by building elevation and foundation type. Societal and hazard conditions probably explain the remaining 20% of variance.

2.2.2 Designing to Exceed 2015 I-Code Requirements for Hurricane Surge

Building new single-family dwellings higher above the BFE than the 1 foot required by the 2015 IRC appears to be cost-effective in coastal surge areas identified as V or VE by FEMA in all states. Surge in coastal V-zones is different from riverine flooding, and so its costs and benefits are different.

When the incrementally efficient maximum (IEMax)[5] of the increase in building height is assessed on a state level, the aggregate BCR (summing benefits and costs over all states) is approximately 7:1, e.g., $7 saved for every $1 spent to build new coastal buildings in V- and VE-zones higher above the shoreline. It would cost approximately $7 million extra to build all new buildings to the IEMax elevation above BFE for 1 year, and would produce approximately $51 million in benefits.

The results strongly suggest that greater elevation of new coastal single-family dwellings in V-zones is widely cost-effective. (The study did not examine greater elevation of buildings in coastal A-zones because of data limitations.) All states have an IEMax building height above code of at least 5 feet. The IEMax elevation is quite high for several reasons. These include the relatively low cost of building a foot higher compared to the price of a house. These costs and benefits refer to building new coastal single-family dwellings higher above BFE, not of elevating existing houses, which would be much more expensive and would result in a lower BCR.

Figure 2-4 illustrates the contribution to benefit from the various benefit categories, led by reduced property loss (about 69%), followed by time-element losses (ALE and indirect BI losses, 19%), insurance (12%), and acceptable costs to avoid deaths and nonfatal injuries at much less than 1%. Figure 2-4 uses state-level estimates for the IEMax elevation above 2015 IRC requirements.

[5] See Section 4.5 for a discussion on the determination of the incrementally efficient maximum as utilized in this study.

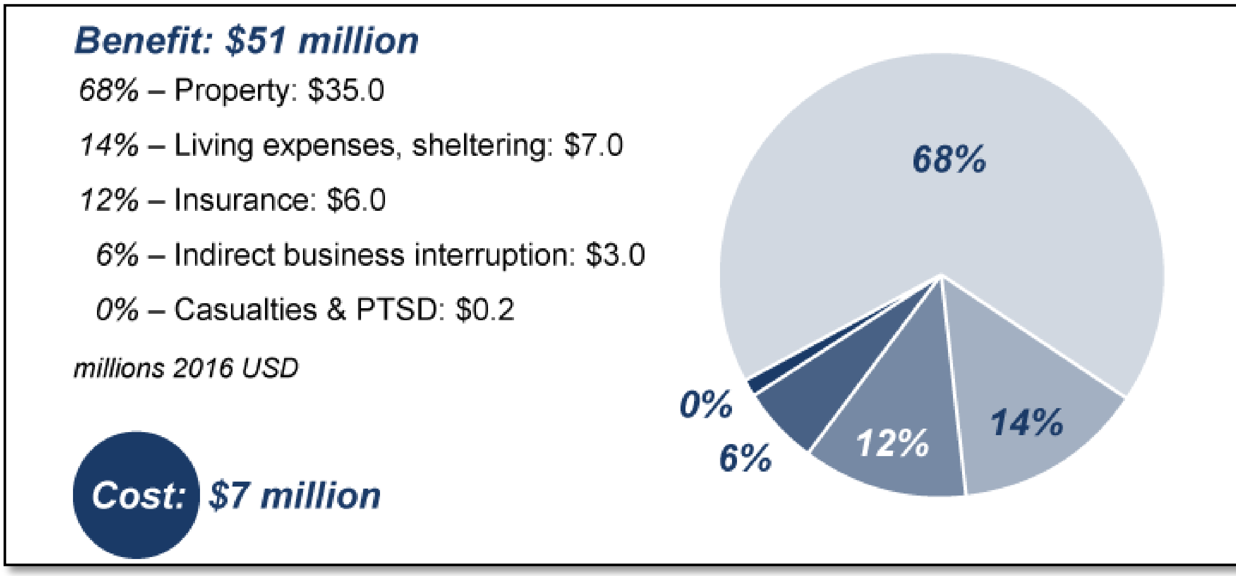

Figure 2-4. Benefits and costs of building new coastal houses in V-zones above 2015 I-Code requirements for 1 year.

The IEMax additional height varies by state, as illustrated in Table 2-3. The benefits of building above code descend from very cost-effective, with a BCR of approximately 17:1 at BFE + 2 ft, to just marginally cost-effective at 8 and 9 feet, with values just above 1. Table 2-3, Figure 2-5 and Figure 2-6 illustrate these results. They show estimated benefits and costs for 1 year of new construction, which as discussed in Chapter 4, are estimated as 1% of the existing building stock in coastal V-zones (not all coastal residences—just those in V-zones).

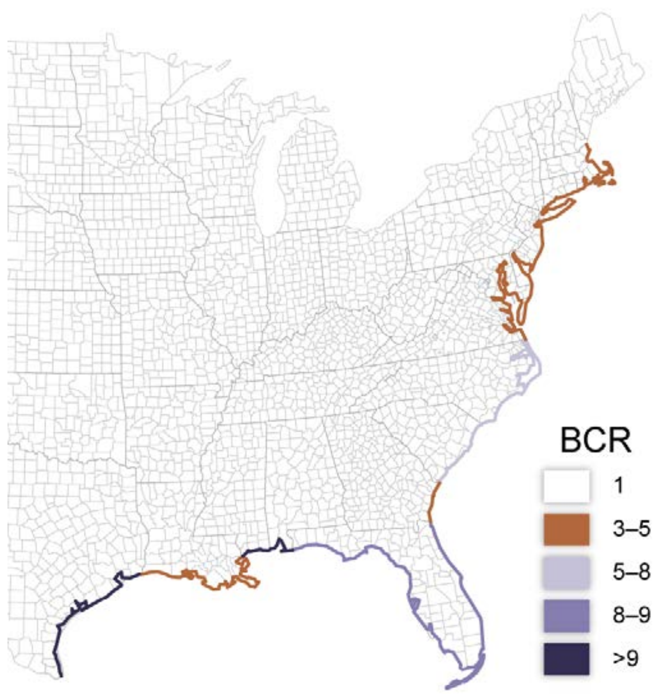

Figure 2-5. BCR of coastal flooding mitigation by elevating homes above 2015 IRC requirements (by state).

Figure 2-6A demonstrates that all building elevations assessed are cost-effective, with diminishing returns. The curve of change in benefit divided by change in cost (ΔB/ΔC) in Figure 2-6B shows that the increase in elevation is cost-effective to 9 feet, with the incremental change in benefit exceeding the incremental change in cost by at least a factor of 1.0 (the threshold indicated by the horizontal dotted line with a y-value of 1.0).

Height (ft)	Property loss	ALE & indirect BI	Insurance fees	Death, injury	Benefit B	Cost C	B/C	ΔB	ΔC	ΔB/ΔC
BFE+2	$ 10.67	$ 2.80	$ 1.81	$0.05	$15.33	$0.90	16.9	$15.33	$0.90	16.9
BFE+3	$ 17.60	$ 4.67	$ 2.99	$0.09	$25.36	$1.80	14.1	$10.02	$0.90	11.2
BFE+4	$ 24.66	$ 6.76	$ 4.19	$0.12	$35.73	$2.71	13.2	$10.37	$0.90	11.5
BFE+5	$ 27.96	$ 7.70	$ 4.75	$0.14	$40.55	$3.60	11.2	$4.82	$0.90	5.4
BFE+6	$ 31.11	$ 8.74	$ 5.29	$0.15	$45.28	$4.50	10.1	$4.73	$0.90	5.3
BFE+7	$ 32.66	$ 9.12	$ 5.55	$0.16	$47.50	$5.41	8.8	$2.22	$0.90	2.4
BFE+8	$ 34.21	$ 9.61	$ 5.82	$0.17	$49.80	$6.30	7.9	$2.30	$0.90	2.6
BFE+9	$ 34.93	$ 9.80	$ 5.94	$0.17	$50.84	$7.20	7.1	$1.04	$0.90	1.2
BFE+10	$ 35.64	$10.07	$ 6.06	$0.17	$51.94	$8.11	6.4	$1.10	$0.90	1.2
BFE+11	$ 35.88	$10.12	$ 6.10	$0.17	$52.27	$9.01	5.8	$0.33	$0.90	0.4

Table 2-3. Benefits and costs of building new coastal 1-story single-family dwellings higher above estimated BFE (all dollar figures in present value, $ millions, for 1 year of new construction).

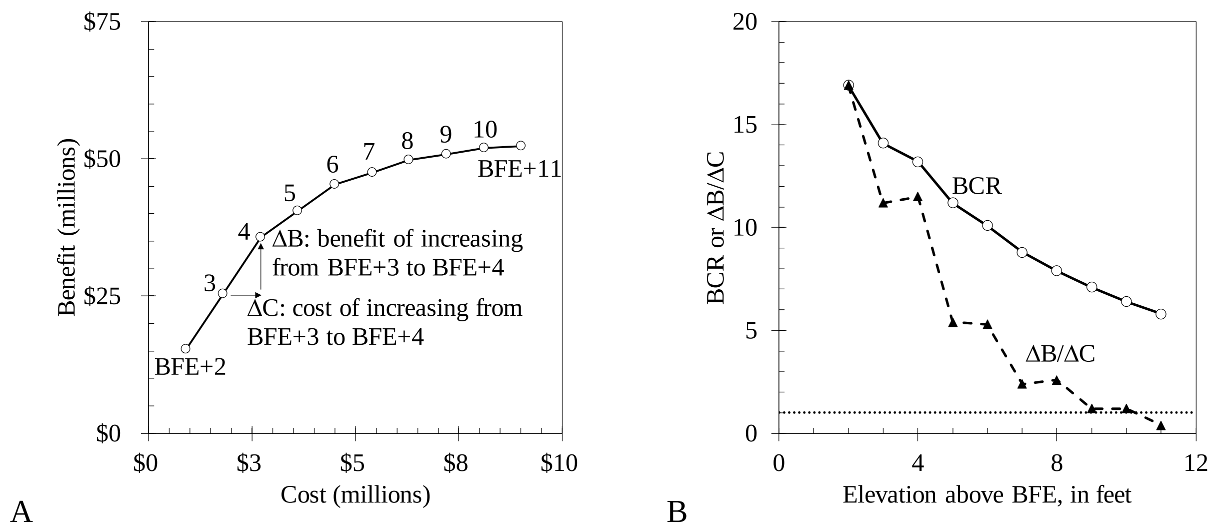

Figure 2-6. Benefits and costs of building new coastal single-family dwellings higher above the requirements of the 2015 IRC: (A) benefits versus costs, (B) BCR and **Δ**B/**Δ**C versus first floor elevation.

State	Height above BFE (ft)	Property ($M)	ALE & indirect BI ($M)	Insurance ($M)	Death, injury ($M)	Benefit ($M)	Cost ($M)	BCR
TX	8	2.18	0.64	0.37	0.01	3.20	0.35	9.1
LA	10	1.49	0.41	0.25	0.01	2.16	0.45	4.8
MS	10	2.32	0.67	0.39	0.01	3.40	0.34	10.1
AL	10	0.79	0.22	0.13	0.00	1.15	0.10	11.7
FL	10	23.19	6.55	3.94	0.11	33.80	4.01	8.4
GA	6	1.22	0.34	0.21	0.01	1.77	0.47	3.8
SC	10	0.09	0.02	0.02	0.00	0.13	0.03	5.0
NC	10	1.99	0.56	0.34	0.01	2.90	0.56	5.2
VA	6	0.02	0.00	0.00	0.00	0.02	0.01	3.8
MD	6	0.01	0.00	0.00	0.00	0.01	0.00	3.8
DE	6	0.02	0.01	0.00	0.00	0.02	0.01	3.8
NJ	6	0.04	0.01	0.01	0.00	0.06	0.02	3.8
NY	6	0.09	0.02	0.02	0.00	0.13	0.03	3.8
CT	6	0.34	0.09	0.06	0.00	0.49	0.13	3.8
RI	6	0.36	0.10	0.06	0.00	0.52	0.14	3.8
MA	6	1.09	0.30	0.19	0.01	1.59	0.40	3.9
Total		35.2	9.9	6.0	0.2	51	7	7

Table 2-4. Summary of IEMax elevations above BFE for new buildings in coastal V-zones, by state, for 1 year of new construction.

Regional differences in BCR and the IEMax elevation generally agree with regional differences in coastal hazard maps. As one might expect, there appears to be a lower BCR where the hazard is lower, such as in the northeastern United States. Even so, the BCRs at the IEMax elevation still exceed 3:1, with the IEMax building height 5 feet above code (BFE + 6) from Virginia to Massachusetts. This might have been harder to believe before Superstorm Sandy. Sandy demonstrated that coastal surge damage can be severe, even in places with only moderate to moderately high wind hazard. The analysis shows that storm-surge heights in these areas constitute a significant hazard, and that reducing that hazard by building higher makes financial sense on a benefit-cost basis.

The project team successfully incorporated NOAA Maximum-of-Maximum Envelope of Water (MOMs) (NOAA, 2014) into a regional probabilistic estimate of storm surge. It was necessary to do so. Using just flood insurance studies (FIS) and FEMA flood maps, one can estimate hazard at the 1% recurrence rate, but the real hazard is uncertain, so actual flood depth with 0.01 annual exceedance frequency might be higher or lower. Modeling losses with the NOAA MOMs (NOAA, 2014), scaled to generally agree with FEMA FIS (FEMA, 2003, 2006a, b, 2007b, c, 2008c, d, 2009a, b, 2012a, b, c, 2013a, 2014b, c) and flood maps (FEMA, 2014d), captures some of the epistemic uncertainty, perhaps providing more-realistic and more-robust BCRs, because of the diversity of data and approaches.

The project team successfully incorporated NOAA (2017a) projections of sea level rise into the BCA. Sea level rise increases the estimated benefit of building higher above BFE because sea level rise adds to storm surge, and higher hazard increases the benefit of mitigation. The benefit of this particular mitigation measure only goes so far. When the sea rises, it extends inland.

When it reaches the building footprint, the ground below is no longer dry on a daily basis, so greater elevation of the first floor provides no more practical benefit.

Including sea level rise increases the BCR by about 10% when using the baseline 2.2% cost-of-borrowing discount rate. Using a higher discount rate such as the 3% and 7% discount rates used by the Office of Management and Budget (OMB) reduces the effect of including sea level rise, because it reduces the recognition of future benefits. The greater the discount rate, the less the model values the future a few decades out, and the less the model recognizes the benefits of greater elevation to mitigate against sea level rise. Section 2.5 examines sensitivity to sea level rise and the discount rate.

The costs and benefits estimated in this *Interim Report* exclude location-specific factors—local variations in construction cost that make one place more or less expensive to build or to pay for repairs than another place. Omitting location cost factors probably may slightly affect total dollar costs and total dollar benefits. The effect is probably small compared with other uncertainties in the analysis.

Location cost factors should affect BCR little if at all. Higher up-front construction cost will tend to accompany higher future repair costs. In locations where future repair costs are greater, mitigation produces greater savings. Thus, higher up-front construction costs occur in the same places as higher future benefits. The two effects cancel out in the BCR, at least for financial costs and benefits, because the same factor would appear in both the numerator and denominator of the BCR. Deaths and injuries are different because they are not affected by location cost factors. The BCR is lower in places where there are higher up-front construction costs and where benefits are dominated by avoided deaths and nonfatal injuries.

Note, finally, that the results presented in this *Interim Report* do not consider social vulnerability, that is, the different degree of harm caused by natural disasters to people who are less able to recover from the disaster owing to lower income, age, etc.

2.2.3 Designing to Exceed 2015 I-Code Requirements for Hurricane Wind

If all new homes were built to the IEMax IBHS FORTIFIED Home program level for 1 year, it would cost approximately $720 million extra and would produce approximately $3.8 billion in avoided future losses. The aggregate BCR (summing benefits and costs over all states) is approximately 5:1, e.g., $5 saved for every $1 spent to build new buildings better along the Gulf and Atlantic Coasts.

Compliance with the IBHS FORTIFIED Home Hurricane program appears to be cost-effective everywhere along the Atlantic and Gulf Coast. As discussed in further depth in Section 4.10.3, the analysis estimates BCR by 10-mph wind speed band, that is, in geographic bands that share a common value with the wind speed in the American Society for Civil Engineers (ASCE) Structural Engineering Institute (SEI) standard ASCE 7-16, *Minimum Design Loads for Buildings and Other Structures* with 700-year mean recurrence interval. The project team considered more than the 700-year wind speed in the calculation of wind hazard. Rather, the analysis attributed the same wind hazard to all locations that share a common value of 700-year wind speed. That is, the analysis considered wind speeds with more-frequent and more-rare recurrence; these contribute to the estimated benefits as well. The following results present estimates of the benefits and costs of 1 year of new construction to exceed 2015 I-Code requirements. (In 1 year, the United States adds or replaces about 1 square foot of buildings for every 100 square feet already in existence, so the costs and benefits of replacing all existing buildings can be calculated by multiplying by 0.01 to reflect 1 year of new construction.)

Table 2-5 presents the IEMax IBHS FORTIFIED Home Hurricane option for each wind speed band. Figure 2-7 illustrates the BCR on a map. The BCR varies from a maximum of 26 for IBHS FORTIFIED Home Hurricane Silver (in locations where 700-year wind speed is 180 mph) to 1.5 for IBHS FORTIFIED Home Hurricane Silver (in locations with 130 mph 700-year wind speed). The IEMax level of certification by location is provided in Figure 2-8. The BCR exceeds 10 where the 700-year wind speed is equal to or greater than 160 mph. These areas, in south Florida and small areas of the Louisiana and Alabama coasts, account for approximately 5% of the population within the scope of the Interim Study. They may be subject to stricter requirements in a local code (e.g. Florida's Miami-Dade and Broward Counties), but the present Interim Study does not consider local codes.

The results show that in places where 700-year wind speed is less than 130 mph, the IBHS FORTIFIED Bronze level is a particularly cost-effective solution to hurricane hazard mitigation, with BCRs from 5.6 to 7.9. In these lower hazard areas, the relative cost of more nails and the use of ring-shank nails are modest compared to the benefits. These simpler measures are required by the 2015 IRC at higher design wind speeds, so at higher wind speeds they do not exceed code requirements, and do not count toward costs and benefits for this piece of the Interim Study.

At design wind speeds greater than 130 mph, FORTIFIED Silver appears to be the most cost-effective option. FORTIFIED Silver calls for protecting openings. FORTIFIED Gold is not applicable in many cases, and is not the IEMax FORTIFIED program for any of the wind bands examined. It is not considered cost-effective at lower levels of design wind speed. However, individual owners may prefer to use Gold for other reasons than achieving a BCR.

The reason the BCR at 120-mph 700-year wind speed is so much higher than at 130 mph is that IBHS FORTIFIED Home Hurricane Bronze requires closer nail spacing for roof-deck attachment at 120 mph than does the IRC: 8d ring-shank nails at 6"/6" (IBHS FORTFIFIED Home Hurricane Bronze) as opposed to 8d smooth-shank nails at 6"/12" (2015 IRC). The cost is small and the benefit is large. At a 700-year wind speed of 130 mph, the 2015 IRC requires the closer nailing, so it bakes the mitigation into the code and there is less for IBHS FORTIFIED Home Hurricane to do.

Figure 2-9 illustrates the contributions from the various benefit categories: first, ALE and indirect BI (45%), followed by building and contents repair costs (39%), and insurance (16%). As outlined in Section 4.16, the insurance benefit results solely from reduced overhead and profit (O&P) costs, not from reduced property losses. O&P is estimated to add 30% to the pure premium associated with property losses. Reducing property losses by $1.00 on an expected annualized basis should decrease O&P charges by $0.30, in the long term, on an aggregate geographic basis. The $0.30 figure is based on an average between 2006 and 2015 of incurred losses and-loss adjustment expenses as a percent of earned premiums, according to the Insurance Information Institute (III 2015).

700-year wind speed (mph)	IEMax FORTIFIED program	Building and contents	Living expenses & indirect BI	Insurance	Benefit	Cost	BCR
110	Bronze	$ 344	$ 373	$ 144	$ 861	$ 154	5.6
115	Bronze	$ 180	$ 196	$ 75	$ 452	$ 81	5.6
120	Bronze	$ 168	$ 182	$ 70	$ 420	$ 53	7.9
130 (> 1 mi)	Silver	$ 64	$ 69	$ 27	$ 159	$ 106	1.5
130 (≤ 1 mi)	Silver	$ 8	$ 8	$ 3	$ 19	$ 13	1.5
140	Silver	$ 146	$ 158	$ 61	$ 365	$ 150	2.4
145	Silver	$ 0	$ 0	$ 0	$ 0	$ 0	3.2
150	Silver	$ 61	$ 109	$ 42	$ 211	$ 47	4.5
160	Silver	$ 519	$ 564	$ 217	$ 1,300	$ 118	11.1
170	Silver	$ 11	$ 12	$ 5	$ 29	$ 2	14.9
180	Silver	$ 4	$ 5	$ 2	$ 11	$ 0	26.6
Total	Mixed	$ 1,505	$ 1,676	$ 646	$ 3,827	$ 724	5

Table 2-5. Benefits and costs for 1 year of new construction at IEMax IBHS FORTIFIED Home Hurricane levels (millions).

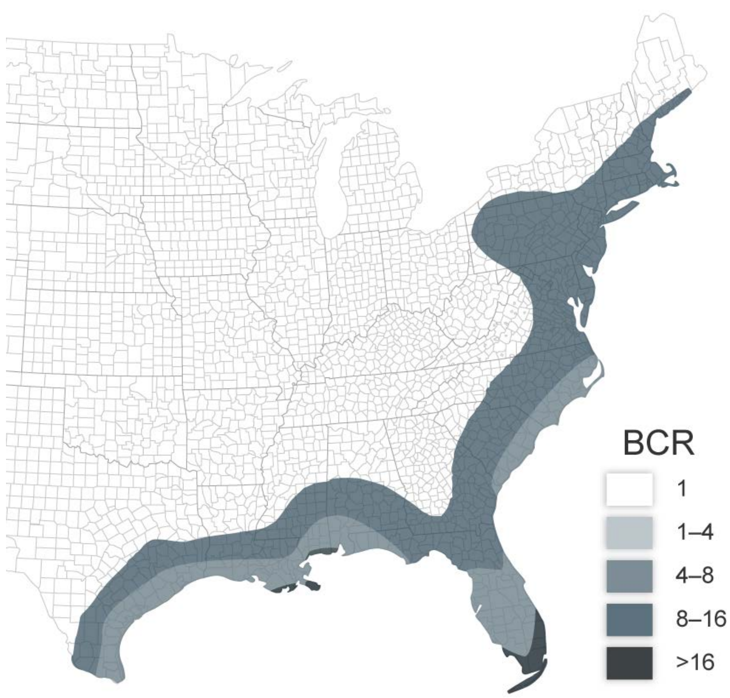

Figure 2-7. BCR of hurricane wind mitigation by building new homes under the FORTIFIED Home Hurricane Program (by wind band).

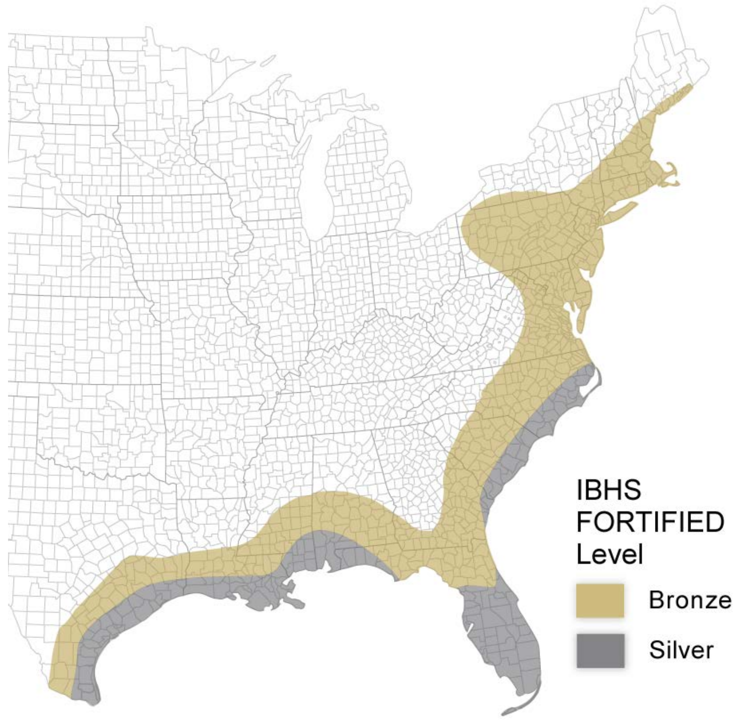

Figure 2-8: Maximum level of the IBHS FORTIFIED Home Hurricane design for new construction where the incremental benefit remains cost-effective.

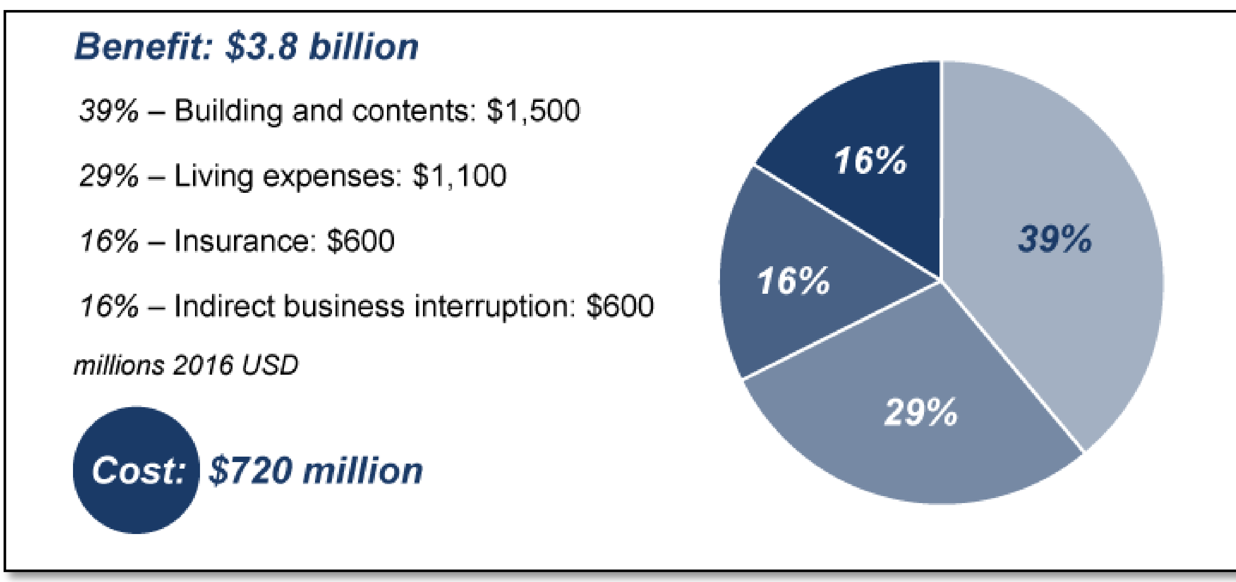

Figure 2-9. Benefits and costs for 1 year of new construction at the IEMax IBHS FORTIFIED Home Hurricane levels.

2.2.4 Designing to Exceed 2015 I-Code Requirements for Earthquake

This section presents the benefits and costs of designing new buildings with strength and stiffness that exceeds the minimum earthquake design requirements of the 2015 IBC. The IEMax strength and stiffness to exceed 2015 I-Code requirements varies from county to county, as does the county-level cost and benefit. In some counties, designing to exceed 2015 I-Code requirements appears to be cost-effective on a BCR basis, in others it does not. Considering just those counties where designing to exceed 2015 I-Code requirements has a county-level BCR greater than 1.0, if all new buildings in all of those counties were built to their county's IEMax level for 1 year, the costs would total approximately $1.2 billion. The sum of the benefits totals approximately $4.3 billion. Dividing the aggregate benefit by the aggregate cost produces an overall average BCR of approximately 4:1, e.g., an average of $4 saved for every $1 spent to build new buildings stronger and stiffer.

Figure 2-10 details the distribution of the benefits that would accrue from 1 year of new construction to the IEMax I_e (the increase in strength and stiffness as a minimum design base shear and minimum design stiffness) value.[6] Approximately half (47%, or $2 billion) accrue from reduced BI (including ALE). About 35% ($1.5 billion) come from reduced property damage. Most of the remainder (18%, $800 million) comes from the U.S. government's acceptable cost to avoid statistical deaths, nonfatal injuries, and PTSD. A small fraction (1%, $30 million) comes from reduced future costs of urban search and rescue. (The project team did not calculate urban search and rescue costs in the BCR for exceeding 2015 I-Code requirements for flood or wind because of its very minor contribution to benefits.)

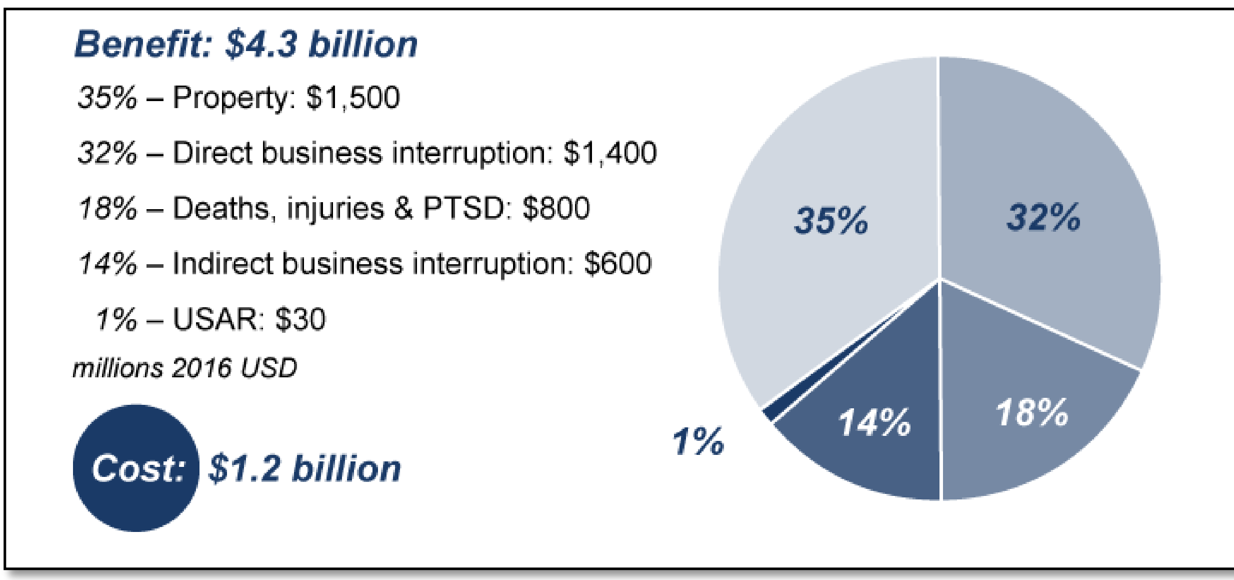

Figure 2-10. Contribution to benefits from exceeding 2015 I-Code earthquake requirements.

[6] The IBC does not define a quantity called minimum design stiffness per se, but rather specifies maximum allowable deformation, which is inversely related to stiffness. The IBC also uses the term I_e differently than the interim study does: as a multiplier for strength but not for stiffness. It is used it here as a multiplier for both strength and stiffness.

Box 2-2. Why Calculate Benefits and Costs Up to I_e = 8?

Some critics may object to evaluating benefits and costs for I_e values as high as 8, and question whether it is even possible to design to such high strengths. It seems possible in many circumstances.

Consider a new 2-story office building in which the seismic force-resisting system relies on special reinforced masonry shearwalls, to use the terminology of ASCE 7-10 Table 12.2-1 (ASCE/SEI 2010). If the building were built in Petaluma, California, at 38.232N -122.615E, on soil of site class D, and it just met strength and stiffness requirements of ASCE 7-10, it would have a seismic response coefficient (design base shear as a fraction of building weight) of C_s = 0.23. Picking up that building and moving it to a certain location in Denver, Colorado, would change its minimum required C_s to be 0.0282g. Since it actually has C_s = 0.23g, it would satisfy design requirements for I_e = 0.23/0.0282 = 8.0. Therefore, engineers could design a new building in Denver to be 8 times as strong and stiff as the 2015 IBC requires.

Furthermore, one could build the Petaluma building 8 times as strong as the 2015 IBC requires for its actual California location. It could be built with less than 200 linear feet in each direction of 8-inch concrete masonry unit walls with 4 ksi masonry and grout and one 60-ksi number-8 bar in each cell. It really is practical (though probably not cost-effective) to design many buildings to remain essentially elastic even at design-level shaking.

It probably does not make sense to design an office building with I_e = 8.0 on the basis of a BCR, but it is possible. Design for site-specific seismic hazard uses risk-adjusted maximum considered earthquake (MCE_R) ground motion maps where spectral acceleration response factor (S_S and S_1) values span almost two orders of magnitude, meaning that the minimum seismic strength in the most highly seismic places are approximately 80 times those of the lowest-hazard places. (S_S = 3.06g near Ridgley, Tennessee, versus 0.037g near Langdon, North Dakota). A factor of 8 is modest compared with the 80-times range of values in design maps.

Certainly, some architectural designs cannot be achieved in very highly seismic areas at very high values of I_e or using certain structural materials. Near the high end of the design maps, it may not be practical to design much stronger. But common cases can be designed to I_e up to at least 3.0, which, as shown later, appears to be approximately the highest value anywhere in the 48 contiguous United States that makes sense on the basis of BCR.

When I_e = 1.0, the design just meets the minimum strength and stiffness requirements of the 2015 IBC. A value of I_e = 3.0 means the building is at least 3 times as strong and stiff as the 2015 IBC requires, and experiences no more than 1/3rd the deformation as the code allows. The project team evaluated benefits and costs for I_e values of 1.0, 1.25, 1.5, 2, 3, 4, 5, 6, 7, and 8. (To understand why so high, see Box 2-2.) The project team also calculated the incremental cost ΔC and incremental benefit ΔB of increasing I_e from 1.0 to 1.25, 1.25 to 1.5, 1.5 to 2.0, etc. The project team calculated the IEMax value of I_e on a census-tract basis; "IEMax" here means the largest value of I_e where ΔB/ΔC > 1.0, e.g., the largest incremental investment in designing to exceed 2015 I-Code requirements that still produces benefits in excess of costs.

The IEMax I_e for approximately 2,700 counties (from a BCR perspective) is 1.0, e.g., current code minimum. For approximately 400 counties however, designing to exceed 2015 I-Code earthquake requirements appears to be cost-effective at the cost-of-borrowing discount rate of approximately 2.2%. Figure 2-11 presents the estimated BCR if all new buildings in the county were designed to the county-level IEMax value of I_e. Figure 2-12 shows each county's IEMax I_e. Counties with the 10 highest county-level BCRs are listed in Table 2-6, all of which are in California. All but San Benito County have a county-level IEMax I_e of 2.0; San Benito County, with a 2010 population of about 100,000 people, has an IEMax I_e value of 3.0.

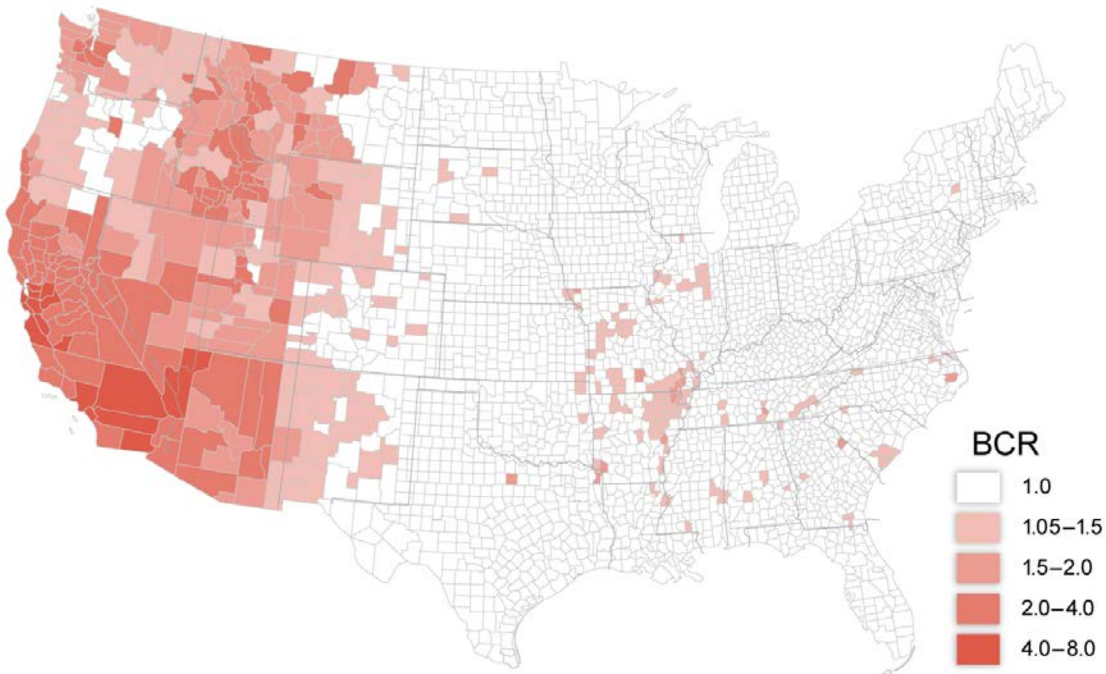

Figure 2-11. BCR of earthquake mitigation by increasing strength and stiffness in new buildings (by county).

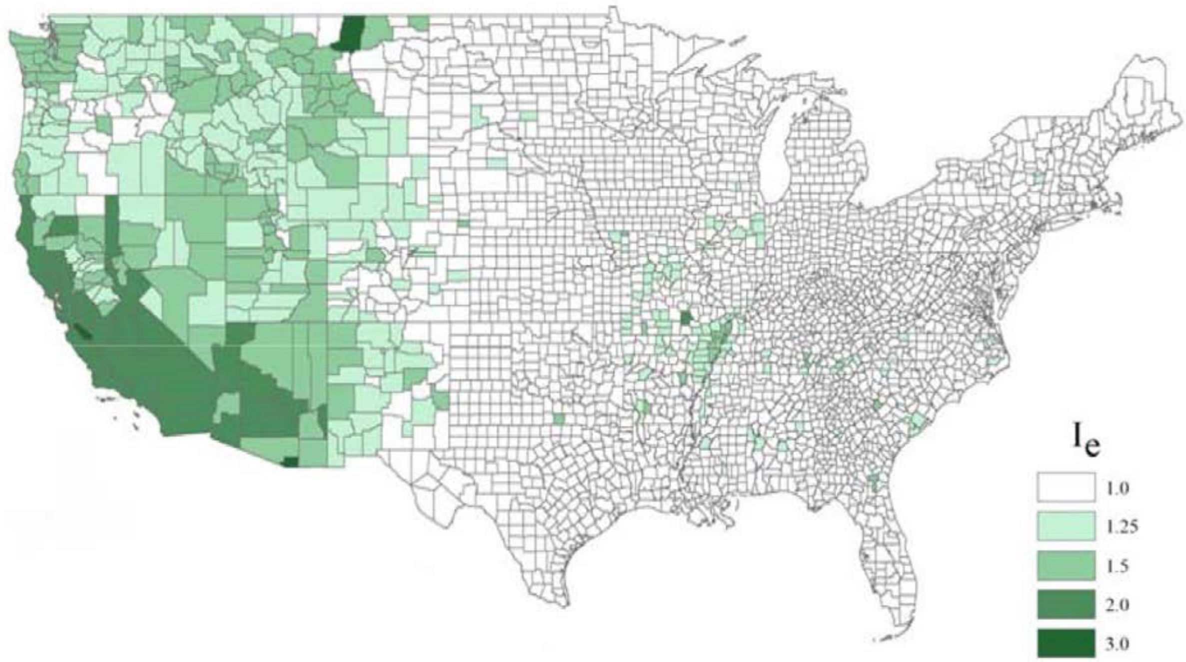

Figure 2-12. Maximum strength and stiffness factor I_e to exceed 2015 IBC and IRC seismic design requirements where the incremental benefit remains cost-effective.

County	State	County-level IEMax I_e	County-level BCR
Imperial	CA	2	7.4
Santa Clara	CA	2	6.0
Monterey	CA	2	5.1
San Bernardino	CA	2	5.0
Alameda	CA	2	4.9
San Joaquin	CA	2	4.7
Los Angeles	CA	2	4.7
San Benito	CA	3	4.7
Riverside	CA	2	4.6
Santa Cruz	CA	2	4.6

Table 2-6. Top-10 counties for designing to exceed 2015 I-Code earthquake requirements.

Table 2-7 summarizes the number of people that benefit from designing new buildings to exceed I-Code minimum strength and stiffness with each of the values of IEMax I_e. Figure 2-13 illustrates the same information. Approximately 100,000 people live in counties where design to three times the minimum strength and stiffness makes economic sense. Approximately 40 million people, 13% of the 2010 population of the United States, live in counties where the IEMax I_e is twice the code minimum. Another 30 million people—10% of the U.S. population—live where it would be cost-effective to design to 25% or 50% greater than code-minimum strength and stiffness. The current code makes economic sense on a benefit-cost basis for about three-quarters of the U.S. population.

IEMax I_e	Counties	2010 population	% of total
1.0	2,674	236,009,947	77%
1.25	253	16,755,955	5%
1.5	126	14,033,579	5%
2	51	39,909,835	13%
3	3	106,942	0.03%
4+	0	0	0%

Table 2-7. Population distribution by county-level IEMax I_e.

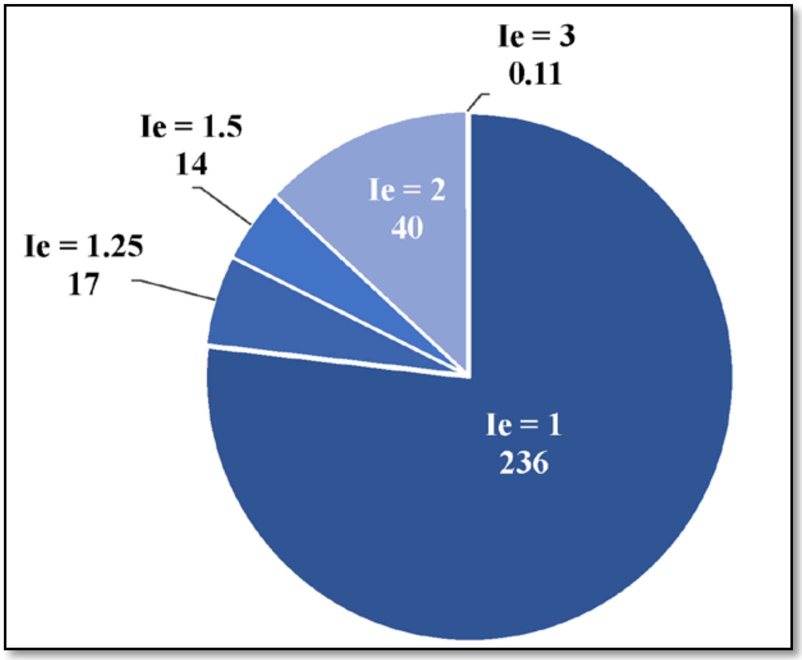

Figure 2-13. Population (millions) by county-level IEMax I_e.

Evaluating Reasonableness of the Results. The results of this *Interim Report* generally agree with intuition. First, the 2005 *Mitigation Saves* study found a BCR for earthquake retrofits on the order of 1.5. It makes sense that incorporating mitigation into new buildings would produce a higher BCR. One might have expected an even larger BCR; an order of magnitude might have seemed reasonable. Perhaps the fact that the BCR is only 4:1 rather than 15:1 can be explained by the fact that new buildings are already strong.

Second, it makes sense that almost half of the mitigation benefit comes from reduced BI, since prior studies such as the ShakeOut scenario (e.g., Jones et al. 2008, pg. 280) suggested that BI losses in a large earthquake can contribute half of the total loss.

Third, it makes sense that BI losses are larger than property losses, since the building code aims to control damage to a limited extent but does not explicitly aim to ensure post-earthquake operability.

Fourth, it makes sense that BCR is higher in California and near large active faults. Greater seismicity means greater chance of incurring, and therefore avoiding, losses. Research for the CUREE-CalTech Woodframe Project (Porter et al. 2006) found similar results for seismic retrofit of older woodframe buildings.

2.2.5 Complying with 2015 IWUIC

If all new buildings built in 1 year in census blocks with BCR > 1 complied with the 2015 IWUIC, compliance would add about $800 million to total construction cost for that year. The present value of benefits would total approximately $3.0 billion, suggesting a BCR of approximately 4:1, e.g., $4 saved for every $1 of additional construction and maintenance cost.

As shown in Figure 2-14, the benefits accrue mostly from reduced property loss ($2.1 billion, 70% of the total), followed by reduced insurance O&P costs ($600 million, 20%), deaths, nonfatal injuries, and PTSD ($150 million, 5% of the total), living expenses and sheltering ($100 million, 3%), and indirect BI ($50 million, 2%).

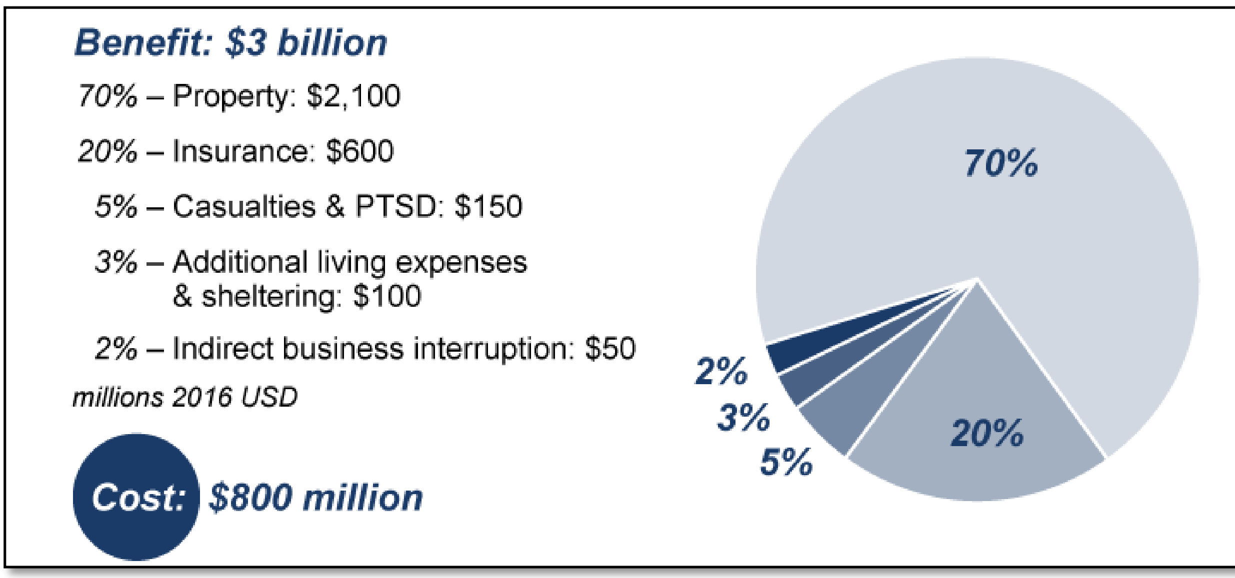

Figure 2-14. Contribution to benefits from 1 year of compliance with the 2015 IWUIC where it is cost-effective to do so.

The project team calculated costs and benefits of complying with the 2015 IWUIC for 47,870 census blocks in four counties in three states: Atlantic County, New Jersey; Alameda County, California; Los Angeles County, California; and Ada County, Idaho. The project team chose these counties to represent a range of fire risk, from moderate (Atlantic County) to high (Alameda and Los Angeles Counties), to extreme (Ada County), based on their burn probabilities (BPs).

The resulting BCR only exceeds 1.0 where the fire risk is moderate or higher. Of the 47,870 census blocks, about 10,000 of them (21%) have a BCR greater than 1.0. Approximately 10.5% have a BCR > 2.6. About 2% have a BCR > 8, and the highest BCR is 15.3.

The project team was interested in examining the total nationwide cost and benefit if the 2015 IUWIC was applied everywhere it was cost-effective. The team performed linear regression of BCR (the dependent variable) against BP (the independent variable), for every grid cell in which BCR > 1 The regression analysis showed some scatter but exhibited a relatively high coefficient of determination $R^2 = 0.85$. Double-checking the regression, the project team found that it reasonably back-estimated the BCR for the four counties. Since BP is available for the entire contiguous United States, the project team used the results of the regression analysis to estimate BCR for every grid cell in all 3,188 counties of the contiguous United States.

Just as only some census blocks have BCR greater than 1, in general, a county can have no place with BCR > 1, or only parts of the county have BCR > 1. Figure 2-15 shows the county-maximum BCR for every county. That is, if a county is shaded other than white in Figure 2-15, there is at least one census block where it would be cost-effective on a BCR basis to implement the 2015 IWUIC, and residents and county officials could reasonably consider implementing the code. In counties that are not shaded in Figure 2-15, it might still make sense to implement the 2015 IWUIC, although not on a BCR basis. Figure 2-15 shows that 761 counties of the 48 states (24% of counties) and 33 of the states (69% of states) have at least a portion with BCR > 1.

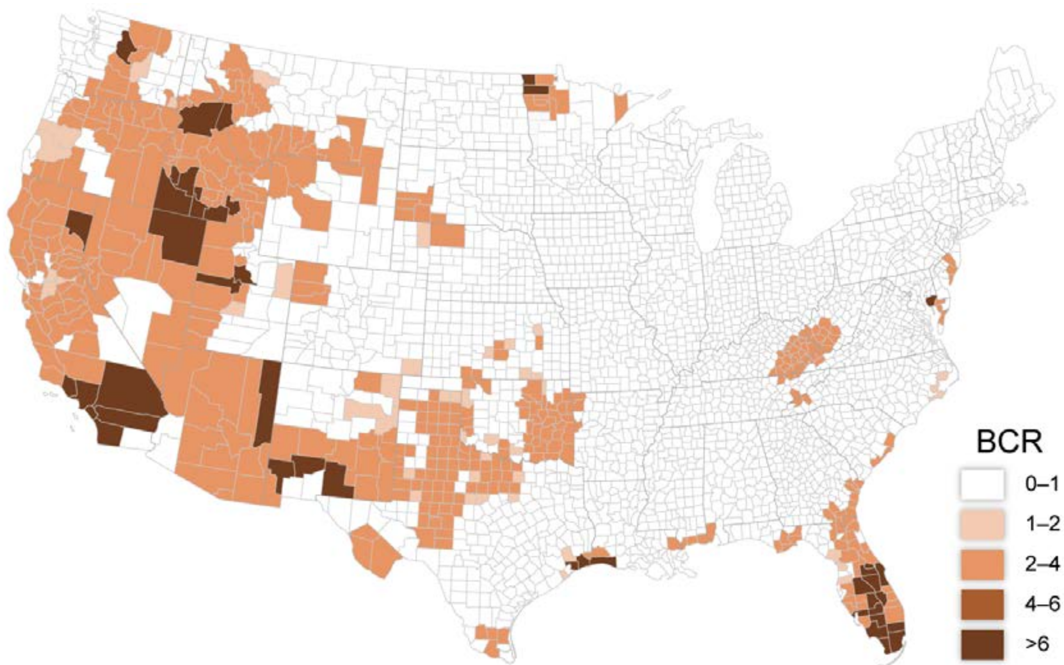

Figure 2-15. BCR of WUI fire mitigation by implementing the 2015 IWUIC for new buildings (by county).

2.2.6 Incentivization

The foregoing estimates of benefits and costs of designing to exceed 2015 I-Code requirements are offered solely to inform mitigation decisions about new buildings, not to advocate for any choice. Benefits, costs, and the BCR represent only a part of the information a decision-maker must consider when deciding among mitigation decisions. Other considerations include resource limitations, recent experience with disasters, community interest, and potentially many other issues. These considerations will vary between communities and individual decision-makers, who must identify, assess, and weigh them based on their own situation.

Not everyone is willing or able to bear the up-front construction costs for more-resilient buildings, even if the long-term benefits exceed the up-front costs. Different stakeholders enjoy different parts of the costs and benefits, and the people who bear more of the costs may argue more urgently than the people who enjoy more of the benefits. However, one set of stakeholders may be able to offer incentives to others to decrease the cost or increase the benefit, and better align the competing interests of different groups.

The MMC and the Institute's Council on Finance, Insurance and Real Estate (CFIRE) have proposed a holistic approach to incentives that can drive coordinated mitigation investments, aligning the interests of multiple stakeholder groups so that they all benefit from a cooperative approach to natural-hazard mitigation. (MMC and CFIRE 2015). Table 2-8 summarizes many such incentives. It shows, by stakeholder group, incentives that the group can enjoy or offer to others to make mitigation more beneficial or less onerous.

Stakeholder	Decision-maker	Incentives	Special costs and benefits
Homeowner	Mortgagor	Reduced insurance premium, tax deduction	Reduced repair costs, reduced chance of mortgage default, accelerated recovery and reduced recovery costs. Some homeowners may be more financially marginal and might be less able to pay extra costs. As a result, the most socially vulnerable people could end up occupying the most structurally vulnerable homes.
Building owner	Corporate real estate manager	Reduced insurance premium, second and later building owners might pay more for resilient buildings, especially if renters would.	Reduced repair costs, reduced chance of mortgage default, accelerated recovery and reduced recovery costs, competitive advantage if others suffer damage.
Occupant	Residential tenant, corporate tenant's chief financial officer or corporate real estate manager, city manager		Enhanced life safety, reduced BI losses, possibly increased content losses. Renters may be more financially marginal. Only higher-income renters would be able to pay these extra costs. As a result, the most socially vulnerable people could end up occupying the most structurally vulnerable rental units.
Builder	Chief executive officer	Builders might promote stronger	Increased construction activity and jobs, more jobs in structural materials

Stakeholder	Decision-maker	Incentives	Special costs and benefits
		buildings if they enjoyed increased market value through higher resilience ratings, design standards modifications, density bonuses or favorable zoning, fee waivers, accelerated permitting	manufacture and distribution. Greater construction costs may or may not be passed on to buyers.
Building official	Chief Building Official	Building officials might advocate for designing to exceed code requirements, but probably face cost pressure from builders	Less demand for post-disaster safety inspection.
City council, county board of supervisors	City council member, mayor, county supervisor		Enhanced public safety, reduced emergency response, accelerated recovery, reduced recovery cost, favorable BCEGS and CRS ratings, jobs, tax revenues, more likely to attract and retain residents and quality developers and businesses.
Insurer, secondary insurer	Chief underwriter; actuary	Reduced portfolio risk	Reduced pure premium, catastrophe risk, a reinsurance costs.
Loan provider	Bank, mortgage company	Increased loan security, asset risk reduction; credit quality of security-backed mortgages	
Financer	Real estate investment trust	Increased financing opportunities, asset risk reduction	
Architect and engineer	Design firms' project managers		Slightly greater fees. Possibly difficult explanations to owners and builders.

Table 2-8. Incentives to implement designing to exceed 2015 I-Code requirements for ordinary (risk-category II) buildings.

2.3 Results from Federal Grants

The previous section addressed the benefits and costs of constructing new buildings in the future to exceed current code requirements. What about the benefits and costs of past federally funded efforts to reduce natural hazard risk in existing buildings (most of which efforts are in public or non-profit buildings)? This section presents results of the project team's analyses of federal grants to mitigate risk from riverine flooding, hurricane and tornado winds, earthquake, and fire at the WUI.

2.3.1 Grants for Flood Mitigation

While the BCR varies between projects, public-sector mitigation spending for the acquisition of buildings exposed to riverine flooding appears to be cost-effective. The average BCR across the sample projects is approximately 7:1; its standard error, 2.0. The implication is that past federally funded riverine flood mitigation is cost-effective (at the cost-of-borrowing discount rate). Given that the total cost of all riverine flood-mitigation grants was $11.5 billion, a BCR of 7:1 implies that federally funded flood mitigation will ultimately save the United States $82 billion.

Based on the distribution of benefits from the various categories within the sample grants, the $82 billion in benefits can be attributed to different categories as shown in Figure 2-16: $53 billion in avoided property losses (65% of the total), $15 billion (18% of the total) in avoided ALE, sheltering, and indirect BI, $9 billion (11%) from reduced administrative costs associated with flood insurance, and the balance of $5 billion (6%) from acceptable costs to avoid deaths, injuries, and PTSD.

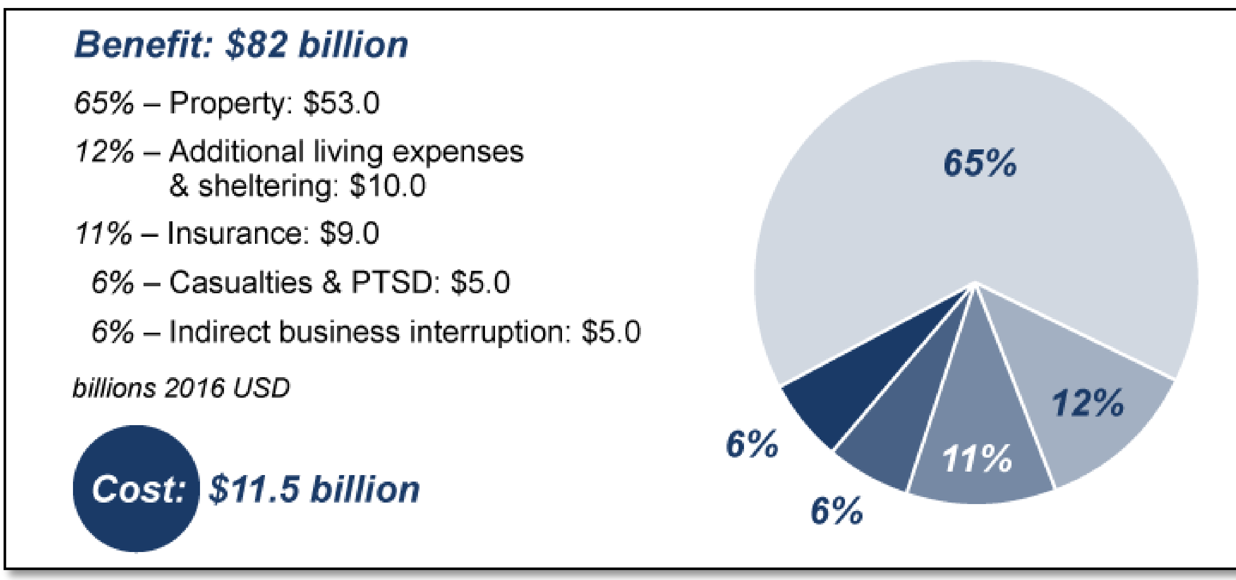

Figure 2-16. Contribution to benefit from federally funded riverine flood grants.

Table 2-9 summarizes benefits and costs of public-sector spending to acquire or demolish flood-prone buildings, especially single-family dwellings, manufactured homes, and 2-4 family dwellings. The results reflect analyses of five projects using Hazus®MH (Hazus) and the baseline cost-of-borrowing discount rate. The table shows project number, location, total mitigation cost, the present value of future probabilistic losses had the mitigation not been undertaken, the present value of losses given that mitigation was undertaken, the difference between the two (e.g., the avoided losses, or benefit), and the BCR.

Results are shown in thousands, rounded to the nearest $10,000. The values in Table 2-8 use the 2.2% cost-of-borrowing discount rate. See Section 2.5 for 3% and 7% discount rates. Results were calculated in 2014 USD but inflated to 2016 USD using a gross domestic product (GDP) deflator (purchasing power parity per capita in international dollars, from the World Bank).

Project	County	Cost	Pre-mitigation loss	Post-mitigation loss	Benefit	BCR
45918	Morgan, IN	$ 2,790	$ 27,710	$ 1,040	$ 26,670	9.6
28096	Wagoner, OK	$ 1,220	$ 19,760	$ 8,030	$ 11,730	9.6
53458	Decatur, GA	$ 950	$ 2,200	$ 0	$ 2,200	2.3
58141 PDM	DeKalb, GA	$ 4,230	$ 8,540	$ 2,500	$ 6,040	1.4
32571	Polk, WI	$ 490	$ 68,720	$ 62,540	$ 6,180	12.5

Table 2-9. Costs and benefits of sampled grants for riverine flood acquisitions (in thousands).

Evaluating Reasonableness of the Results. The sample-average BCR of 7:1 is higher than the 5:1 figure for riverine flood estimated in the 2005 *Mitigation Saves* study. Considering variability between grants, agreement within 40% is satisfactory, and tends to support the conclusion that flood-mitigation is cost-effective. The fact that the *2017 Interim Report* estimate is higher than in the 2005 study is perhaps attributable to Hazus**.** The project team used the Hazus flood module here, whereas the authors of the 2005 study used fairly cautious and approximate methods because their work began before the availability of a fully functioning Hazus flood module. In the face of great uncertainty, the authors of the 2005 *Mitigation Saves* study decided to err on the side of underestimating losses.

One more observation about Table 2-9: the per-building cost of the Georgia grant was more than three times those of the Indiana and Oklahoma grants, which seems questionable. It may be that the available data omit some buildings from the acquisition, or that they were miscoded and appear elsewhere in the database. In either case, the analysis would underestimate the benefit and therefore the BCR. If true, the accurate BCR for the Georgia grant would be closer to that of most of the other grants, and the overall average would be higher.

2.3.2 Grants for Wind Mitigation

Federal grants to mitigate wind damage are highly cost-effective. In 23 years, public entities have spent $13.6 billion to mitigate future wind losses; these efforts will ultimately save the United States an estimated $70 billion in avoided property losses, ALE, business impacts, and deaths, injuries, and PTSD. Their total BCR is approximately 5:1.

Table 2-10 presents the benefits of mitigating wind damage. The low- and medium-hazard projects focused primarily on life safety. These life-safety focused projects produce very large benefits, primarily because of the acceptable cost to avoid a statistical fatality ($9.5 million) and smaller but still fairly large acceptable costs to avoid nonfatal injuries, and because this analysis does not discount human life. Figure 2-17 details the contribution to overall benefits from the various benefit categories considered here.

	Low hazard	Medium hazard	High hazard	Overall
BCR	6.2	6.5	3.3	5
Total stratum cost	$ 1,580	$ 6,550	$ 5,450	$ 13,580
Total stratum benefit	$ 9,860	$ 42,440	$ 17,930	$ 70,230

Table 2-10. Costs and benefits of sampled federal grants to mitigate wind damage (in millions).

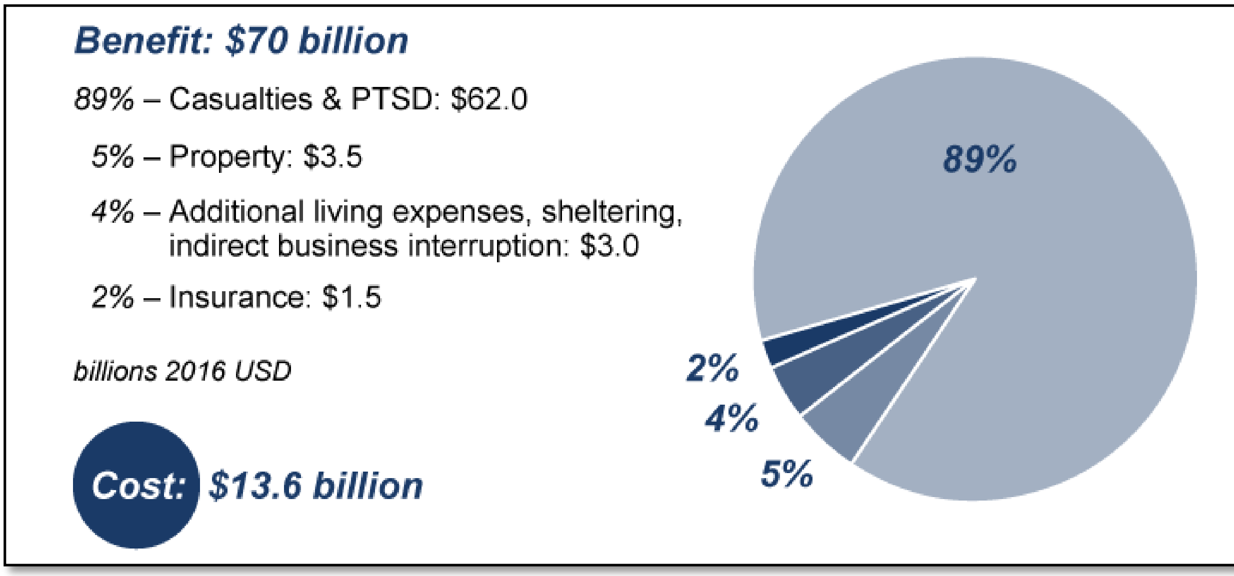

Figure 2-17. Contribution to benefit from federally funded wind grants.

Not every life-safety mitigation project results in a BCR greater than 1.0, but that might have as much to do with the available data as with the actual mitigation effort undertaken. The estimated BCR depends largely on the level of hazard, alternative use of the facility, and accessibility. In-home safe rooms generally appear to be cost-effective, exhibiting an average BCR of 4.25. Large facilities with dual purposes, such as school gymnasia and cafeterias, exhibit an average BCR of 8.0. In these cases, the cost of mitigation is simply the additional cost of hardening the facility.

Accessibility and use also strongly affect cost-effectiveness. For example, a shelter located at a hospital will likely protect life at any time of day throughout the year. By contrast, for much of the year and many times of day, nobody is likely to be near enough to need a small shelter in a large park. On a probabilistic basis, such shelters provide lower benefits.

The location of the hazard mitigation effort matters too. The same kind of wind-mitigation efforts in Oklahoma produce higher estimated benefits than they do in North Dakota. The kind of mitigation matters as well. Shutters appear to be highly cost-effective, particularly those that protect valuable equipment at utilities or industrial facilities. Shutters for ordinary public buildings without high-value contents produce a lower but still impressive BCR (about 3.5).

The challenge for the project team is that the members had to estimate the benefits of county-wide residential retrofitting projects without data specifying exactly what was done to each building. The project team identified likely mitigation efforts for older and newer buildings, and used the American Community Surveys (USCB 2010-2014) to estimate the number of homes built before and after major code changes, especially the implementation of the *Florida Building Code* (FBC) in 2002 (ICC 2015). County-wide residential retrofit projects resulted in a BCR of 1.5 to 3.5.

Evaluating Reasonableness of Results. The 2017 project team produced a 33% larger BCR for wind mitigation than in the 2005 *Mitigation Saves* study, e.g., 5:1 (Interim Study) versus 4:1 (2005 *Mitigation Saves* study). The difference can be attributed largely to the longer period over which the Interim Study recognizes mitigation benefits: 75 years versus 50 years in the 2005 *Mitigation Saves* study. At an approximate 2.2% annual discount rate for cost of borrowing, a 75-year annuity is worth about 21% more than a 50-year annuity with the same coupon payment. The remaining 10% difference could be a function of the uncertainty associated with this sampling strategy.

2.3.3 Grants for Earthquake Mitigation

Considering mitigation costs totaling $2.2 billion, the average BCR of approximately $3 to $1 implies that federally funded earthquake hazard mitigation between 1993 and 2016 saves society $5.7 billion, in approximately the proportions shown in Figure 2-18. Note that few buildings are insured for earthquake shaking, so the analysis ignores insurance benefits.

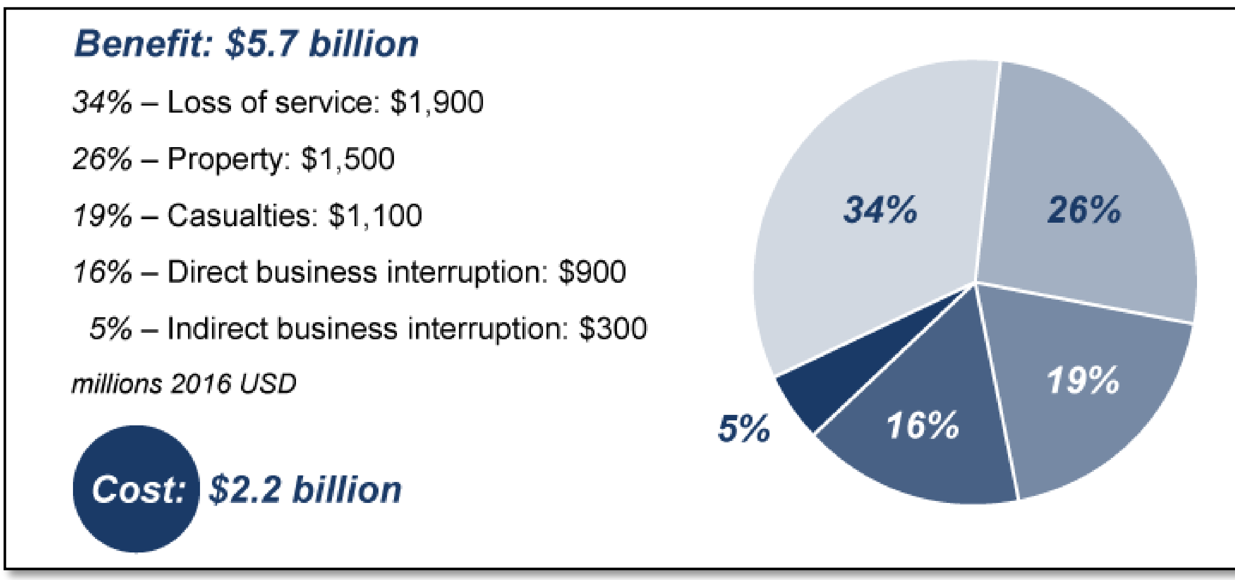

Figure 2-18. Contribution to benefit from federally funded earthquake mitigation grants.

The analysis produces a standard error of BCR equal to 0.56, which measures uncertainty in the stratum-average BCR. It suggests that, with more than 99% confidence, the true population-average BCR exceeds 1.0. The sample strongly suggests that 23 years of federally funded earthquake mitigation of public buildings has been cost-effective. It will save the public more than it cost, on average, over the long run, which is the basis of BCA, even for earthquakes.

Evaluating Reasonableness of the Results. This section examines the estimated benefits of federal grants supporting earthquake risk mitigation, beginning with a comparison with the 2005 *Mitigation Saves* study. The estimated BCR of 3:1 (2.6:1 when shown with more precision) is

73% higher than the 2005 estimate of 1.5. The project team attributed some of the difference (21%) to recognizing benefits over 75 years rather than 50 years. The team attributed most of the remaining difference to the new ability to estimate the value of loss of service to the community—a capability of FEMA's BCA (Benefit Cost Analysis) Tool that was not available for the 2005 *Mitigation Saves* study. As shown in Figure 2-18, loss of service represents approximately one-third of the estimated benefits. If one omits loss of service and reduces all other benefit categories by a factor of 1.21 to reflect a 50-year life versus 75 years, the BCR would be 1.43, almost the same as in 2005. The similarity tends to support the new figure.

Discussion. A linear regression of BCR against project cost within the sample of 23 projects reveals a low coefficient of determination: $R^2 = 0.03$, suggesting that BCR is not linearly related to project cost. That is, spending more does not necessarily save disproportionately more. (Nor does the other way hold true: spending less does not save more either.)

The nature of the mitigation efforts seems more closely related to the BCR. The most apparently cost-effective mitigation efforts address utilities and other lifelines: electrical substations, hospitals, and fire stations (average BCR of 4.5), followed by education (1.7), then public administration and other miscellaneous efforts (about 1.0).

It may be that the analysis underestimates the BCR for the last category, especially if public administration provides public services after an earthquake that are too intangible to be quantified yet by the FEMA BCA Tool. The orderly operation of government seems more important in the immediate aftermath of a natural disaster than at other times. Therefore, the benefits associated with efficient government in the immediate aftermath of a disaster may represent an omitted benefit category.

Also, it seems likely that having operating schools matters a lot in the aftermath of an earthquake, so parents do not need to interrupt work to care for children because school is closed. A BCR of 1.7 might therefore underestimate the true BCR for mitigating public-school buildings, because it omits a benefit category for childcare. Viewed another way, if one parent in a two-income household has to stop work to care for children while their school is nonfunctional, the indirect BI would increase. This fairly indirect cost is probably not reflected in the indirect BI cost to the economy conditioned on loss of function in education.

As with the 2005 study, property benefits alone do not equal mitigation cost, but the sum of property and casualties do. By adding other societal benefits—BI losses and especially loss of service to society—earthquake mitigation more than pays for itself. That observation reinforces the notion that earthquake risk mitigation broadly benefits society. That is, the benefits of strengthening one building extend far beyond the property line: the benefits also go to the families of the people who work in the building and to the community that the building serves.

2.3.4 Grants to Mitigate Fire at the WUI

This section presents estimates of the costs and benefits of federally funded efforts to mitigate fire at the WUI. The project team used many of the same principles and processes to analyze mitigation grants as it did for analyzing above-code measures. With a total project cost of approximately $56 million (inflated to 2016 USD), federally supported mitigation of fire at the WUI will save society an estimated $173 million in avoided future losses. Applying the relative contribution from benefit categories calculated in the above-code measures study yields Figure 2-19, which shows the estimated contribution of benefits produced by federally funded grants to mitigate fire risk at the WUI.

For reasons explained in Chapter 5, the project team used results of above-code measures to impute a BCR for many grants in the sample. The project team imputed the BCRs for making a typical single-family dwelling comply with the 2015 IWUIC to federal mitigation grants such as replacing private residential roofs (with a requirement for vegetation management) and to grants associated with vegetation management.

In summary, of the 25 grants with sufficient data available, the project team estimated BCRs for four on the basis of project-specific, and imputed BCRs for 21 using results from above-code measures based solely on grant location. Of the former four, two had a BCR greater than 1.0; two, less than 1.0. Of the 21 latter grants, eight had BCRs greater than 1.0; 13 had BCRs less than 1.0. In some cases, the properties were close to a boundary between locations with BCRs of greater than 1.0 and less than 1.0. Given issues of locational accuracy and uncertainty in the above-code study results, the BCRs determined using these results are only approximate. For the 25 grants with sufficient data, the analysis produced an average BCR of approximately 3:1.

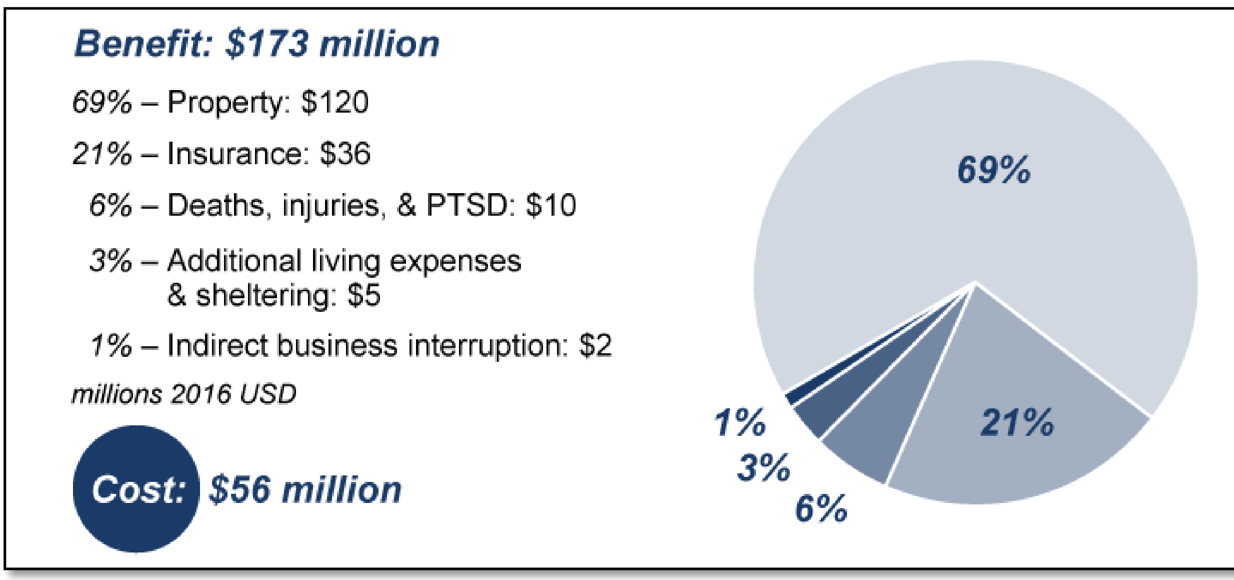

Figure 2-19. Contribution to benefit from federally funded WUI fire mitigation grants.

2.4 Aggregate Benefits and Costs

The project team identified a methodology to estimate aggregate benefits and costs associated with the mitigation strategies. Table 2-11 recaps the costs and benefits presented earlier in this chapter, in terms of billions of dollars and BCR. Again, the rows for exceeding I-Code requirements for 1 year refer to the overall long-term costs and benefits accruing from 1 year of new construction of new buildings to exceed I-Code requirements, not the benefits associated with 1 year of reduced risk. However, as each additional year of construction is implemented, the cost and benefit amounts will increase, with the overall BCR likely to remain close to the same, barring changes in any of the variables.

If all new buildings were built to the IEMax design to exceed 2015 I-Code requirements for 1 year, new construction would save approximately $4 in avoided future losses for every $1 spent on additional, up-front construction cost. The project team determined the total costs and benefits for 1 year of design to exceed 2015 I-Code requirements by totaling the benefits and costs of the 5 mitigation categories in Table 2-11. Figure 2-20 shows the contributions to the calculation of these benefits.

Mitigation category	Cost (billions)	Benefit (billions)	BCR
Exceed 2015 I-Code requirements for riverine flood for 1 year	$0.91	$ 4.30	5
Exceed 2015 I-Code requirements for hurricane surge for 1 year	$0.01	$ 0.05	7
Exceed 2015 I-Code requirements for hurricane wind for 1 year	$0.72	$ 3.80	5
Exceed 2015 I-Code requirements for earthquake for 1 year	$1.20	$ 4.30	4
Comply with 2015 International IWUIC Code for 1 year	$0.80	$ 3.00	4
Total, 1 year of design exceeding 2015 I-Code requirements	**$3.6**	**$15.5**	**4**

Table 2-11. Costs and benefits associated with constructing new buildings in one year to exceed 2015 I-Code requirements (in $ billions).

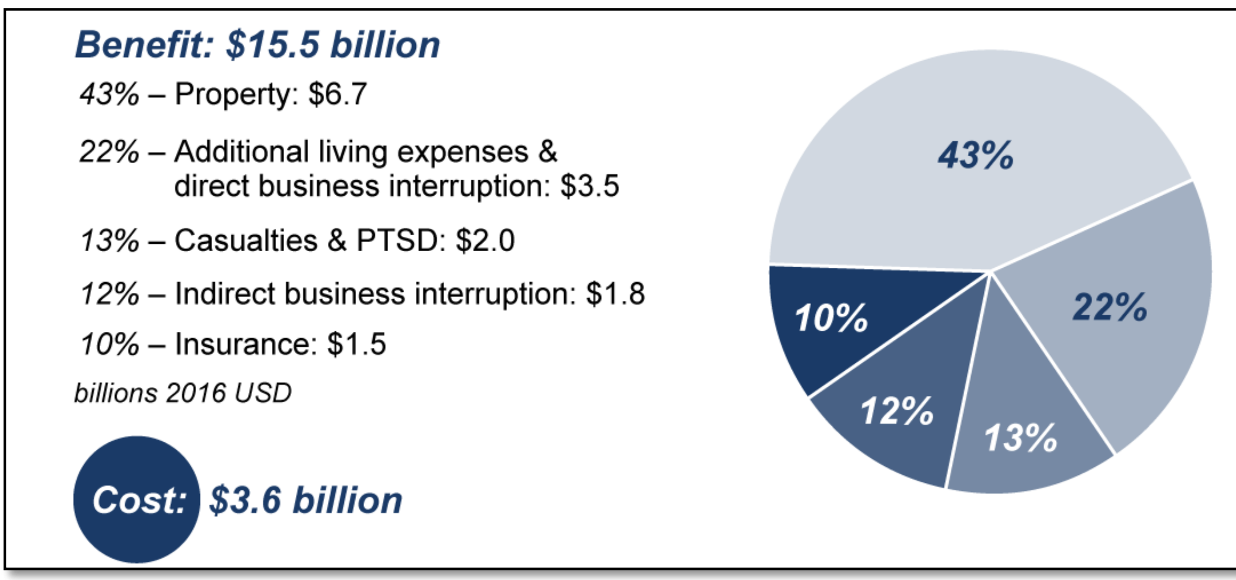

Figure 2-20. Total costs and benefits of new design to exceed 2015 I-Code requirements.

Considering the subtotal for the past 23 years of federally funded natural hazard mitigation, at the 2.2% cost-of-borrowing discount rate, the program team's analysis suggests that society will ultimately save $6 for every $1 spent on up-front mitigation cost. Figure 2-20 shows the contributions to the calculation of these benefits.

Mitigation category	Cost (billions)	Benefit (billions)	BCR
Grants for riverine flood 1993-2016	$ 11.50	$ 82.00	7
Grants for wind 1993-2016	$ 13.60	$ 70.00	5
Grants for earthquake 1993-2016	$ 2.20	$ 5.70	3
Grants for fire at WUI 1993-2016	$ 0.06	$ 0.17	3
Total from federal grants 1993-2016	**$ 27.4**	**$157.9**	**6**

Table 2-12. Costs and benefits associated with 23 years of federal grants (in $ billions).

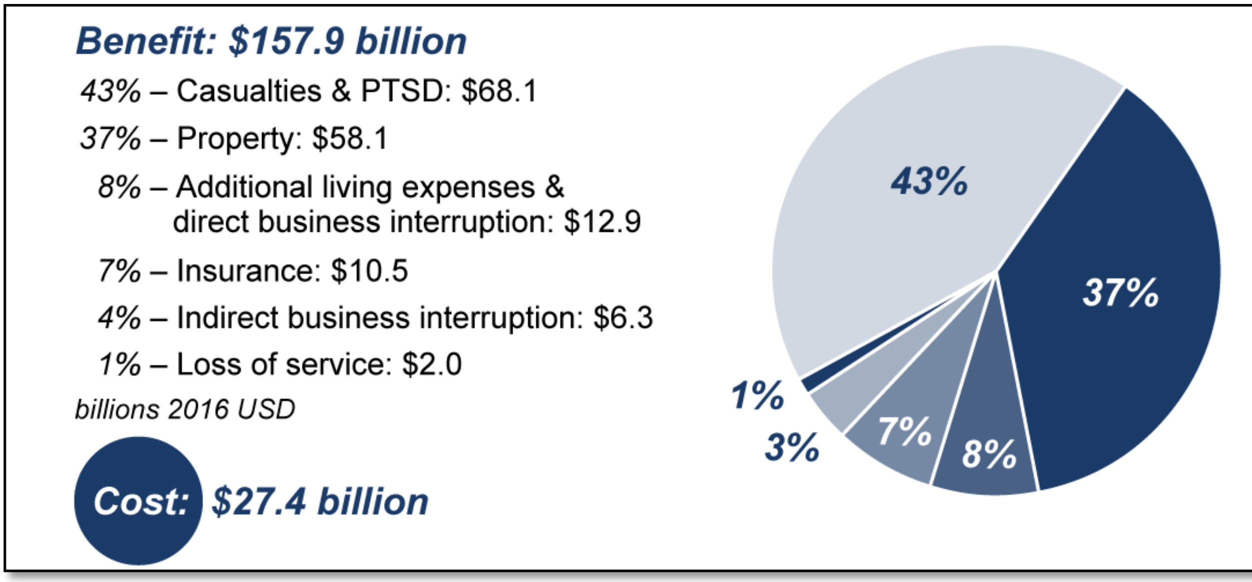

Figure 2-21. Total costs and benefits of 23 years of federal mitigation grants.

2.5 Recap of Interim Study Findings

To recap, first, all nine categories of natural hazard mitigation studied to date appear to be cost-effective, with BCRs varying between 3:1 and 7:1. They show once again that natural hazard mitigation saves, both in the private and public sectors, and for a variety of perils. Second, the subtotals for designing to exceed 2015 I-Code requirements in the future and 23 years of past grants show that both broad categories of natural hazard mitigation also appear to be cost-effective, with BCRs of 4:1 and 6:1, respectively. These results mean that society can cost-effectively protect itself from natural hazard risk in multiple ways, both by mitigating past problems and by preventing future ones. Third, all major stakeholder groups enjoy net benefits from new design to exceed code requirements for flood, wind, and earthquake, and to comply with the 2015 IWUIC in the case of fire.

2.6 Natural Hazard Mitigation Saves in Every State

Considering the past 23 years of federal grants to mitigate flood, wind, earthquake, or fire at the WUI, every state in the contiguous United States is estimated to save at least $10 million in avoided future losses. Most states will save at least $1 billion, and four—Louisiana, New Jersey, New York, and Texas—will save at least $10 billion in avoided future losses. See Figure 2-22.

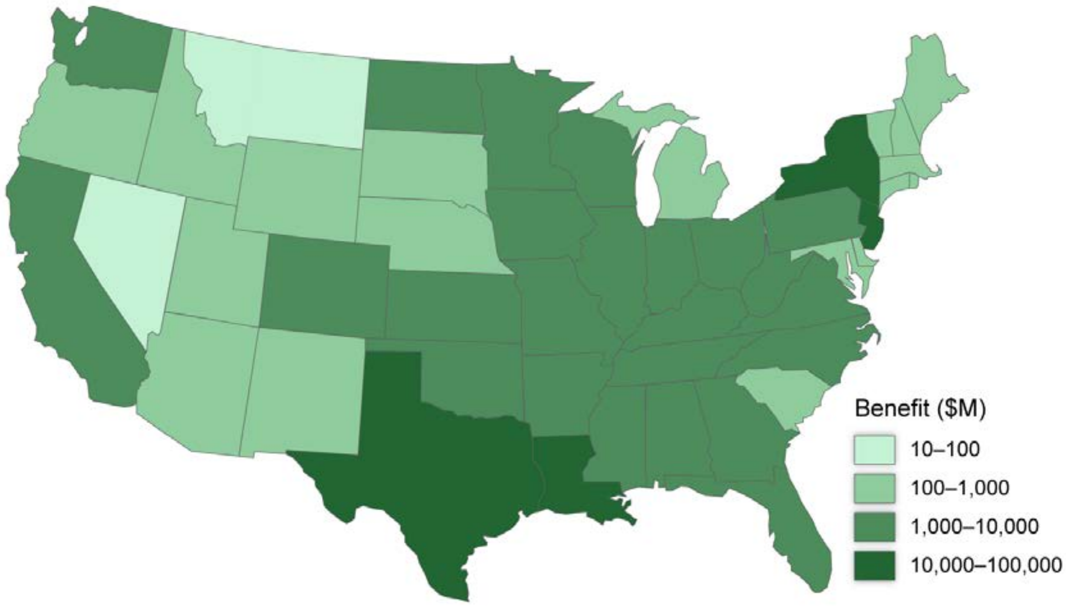

Figure 2-22. Aggregate benefit by state from federal grants for flood, wind, earthquake, and fire mitigation.

2.7 All Stakeholders Benefit from Exceeding 2015 I-Code Requirements

The project team set out to determine who wins and who loses when it came to designing to exceed 2015 I-Code requirements, and found that there are no losers, at least on average, in the long run, at the broad level of these stakeholder groups. Figure 2-22 shows that all four categories of designing to exceed 2015 I-Code requirements—for flood, wind, earthquake, and fire at the WUI—produce positive net benefits to developers, title holders, lenders, tenants, and the community. All of society wins when builders make new buildings meet an IEMax level of design to exceed 2015 I-Code requirements. Remember, that means not building to exceed 2015 I-Code requirements where it does not make financial sense, on a societal level, to do so. The benefits to tenants and owners only accrue to those who own or occupy buildings designed to exceed 2015 I-Code requirements, not, for example, to the people who live or work in older buildings or buildings that are not designed to exceed I-Code requirements. However, even those who do not own or occupy those buildings enjoy a share of the community benefits. (See Section 4.21 for an in-depth examination of stakeholder benefits.)

Figure 2-23. Stakeholder net benefits resulting from one year of constructing all new buildings to exceed select 2015 IBC and IRC requirements or to comply with 2015 IWUIC.

2.8 Synergies Across Mitigation Strategies

Synergies exist where two or more dissimilar mitigation actions are undertaken at a single facility or single system of facilities. "Dissimilar mitigation actions" means those that attempt to mitigate risk in different ways, such as combining efforts to strengthen an existing building using above-code measures with emergency planning for the same facility. A system of facilities refers to facilities that interact in important ways, such as the different buildings on a medical campus. While the project team examined systems of facilities, such as two buildings on the University of California San Francisco medical campus for the federal grant earthquake mitigation sample, the project team did not examine cases where two or more dissimilar mitigation actions have been undertaken at them.

Moving forward, the project team might examine synergies, but they do not yet apply. Section 4.20 and Equations 4-47 through 4-49 present the methodology for aggregating multiple mitigation efforts. Currently, there are no higher-order terms, so all values of $m = 0$, so there is nothing to the right of the first summation on the right side of the equation. Possible exceptions that have not been quantified:

- Designing to exceed 2015 I-Code earthquake requirements should reduce losses resulting from fire following an earthquake. Strengthening and stiffening a building to better resist earthquake damage will also tend to reduce damage to its fire-resistive features and thus reduce damage from fire following an earthquake. However, the present loss estimates for designing to exceed 2015 I-Code requirements do not include fire losses.
- Widely adopting the 2015 IWUIC for new buildings (as in the study of above-code measures) would tend to reduce losses to existing buildings (as under federal mitigation

grants) in the same neighborhood. The phenomenon resembles a preventive anti-epidemic measure to prevent occurrence and spread of infectious disease in a population.

- Designing to exceed 2015 I-Code earthquake requirements should reduce losses resulting from wind. Similarly, adopting an IBHS FORTIFIED Home Hurricane measure might reduce earthquake losses. Both measures improve the building's ability to resist lateral forces. The synergy benefit is likely to be small or negligible for the cases examined here because of details of the load path. The benefit would be more significant for manufactured homes, especially the addition of an engineered tie-down system to an otherwise unrestrained manufactured home.

2.9 Applying Alternative Discount Rates

2.9.1 OMB Discount Rates

OMB procedures call for BCAs to be performed considering a 3% discount rate and a 7% discount rate to reflect the time value of money. Using a 3% discount rate and a 75-year useful life of a new building reduces the present value of monetary benefits by about 19%, e.g., the present value of monetary benefits under a 3% discount rate is about 0.81 times the present value at the cost-of-borrowing discount rates documented in Appendix H of this Interim Study. Using a 7% discount rate for monetary benefits produces a present value of monetary benefits equal to about 0.39 times the present value of benefits at the cost-of-borrowing discount rate. The analysis does not discount deaths, nonfatal injuries, or PTSD for reasons discussed in the 2005 *Mitigation Saves* study and elsewhere in this Interim Study. As a consequence, benefit totals that include both monetary and non-monetary benefits do not scale by 0.81 or 0.39, for 3% or 7% discount rates respectively. Table 2-13 and 2-14 present the BCRs found at multiple discount rates.

Mitigation category	BCR at Various Discount Rates		
	2.2%	3%	7%
Exceed 2015 I-Code requirements for riverine flood	5	4	3
Exceed 2015 I-Code requirements for hurricane surge	7	6	3
Exceed 2015 I-Code requirements for hurricane wind	5	4	2
Exceed 2015 I-Code requirements for earthquake	4	3	2
Comply with 2015 IWUIC	4	3	2
Total, 1 year of exceeding 2015 I-Codes	**4**	**4**	**2**

Table 2-13. Total BCR of exceeding 2015 I-Codes at various discount rates.

Mitigation category	BCR at Various Discount Rates		
	2.2%	3%	7%
Grants for riverine flood	7	6	3
Grants for wind	5	5	5
Grants for earthquake	3	2	1.3
Grants for fire at WUI	3	2	1.3
Total, 23 years of grants	**6**	**5**	**4**

Table 2-14. Total BCR of federal mitigation grants at various discount rates.

2.9.2 Calculating BCRs with a 3% Discount Rate

Using a 3% discount rate to reflect the time value of money produces the total costs and benefits shown in Tables 2-15 and 2-16, expressed in billions of dollars. The benefit in each category is smaller than using a cost-of-borrowing discount rate and the aggregated benefits are smaller ($12.9 billion rather than $15.5 billion and $139.8 billion rather than $157.9 billion respectively), but even at the higher discount rate, natural hazard mitigation still appears to be cost-effective in every category.

If all new buildings were built to the IEMax, above-code design for one-year, new construction would save approximately $4 in avoided future losses for every $1 spent on additional, up-front construction cost. Actually, the 3.6 BCR underestimates the true BCR, since it assumes the same degree of design to exceed 2015 I-Code requirements as estimated for the IEMax design at the cost-of-borrowing discount rate. With the higher discount rate, fewer locations would be designed to higher levels, and both costs and benefits would drop, rather than just costs. In any case, designing to exceed 2015 I-Code requirements remains cost-effective in all five categories.

Considering the total for the past 23 years of federally funded natural hazard mitigation at a 3% discount rate, society ultimately saves approximately $5 for every $1 spent.

Mitigation category	Cost (billions)	Benefit (billions)	BCR
Exceed 2015 I-Code requirements for riverine flood	$ 0.91	$ 3.67	4
Exceed 2015 I-Code requirements for hurricane surge	$ 0.01	$ 0.04	6
Exceed 2015 I-Code requirements for hurricane wind	$ 0.72	$ 3.08	4
Exceed 2015 I-Code requirements for earthquake	$ 1.13	$ 3.59	3
Comply with 2015 IWUIC	$ 0.80	$ 2.48	3
Total, 1 year of exceeding 2015 I-Codes	**$ 3.6**	**$ 12.9**	**4**

Table 2-15. Total cost, benefit, and BCR of exceeding 2015 I-Codes, using a 3% discount rate.

Mitigation category	Cost (billions)	Benefit (billions)	BCR
Grants for riverine flood	$ 11.50	$ 66.37	6
Grants for wind	$ 13.60	$ 68.48	5
Grants for earthquake	$ 2.20	$ 4.83	2
Grants for fire at WUI	$ 0.06	$ 0.14	2
Total, 23 years of grants	**$ 27.4**	**$ 139.8**	**5**

Table 2-16. Total cost, benefit, and BCR of federal mitigation grants, using a 3% discount rate.

2.9.3 Calculating BCRs with a 7% Discount Rate

Using a 7% discount rate to reflect the time value of money produces the total costs and benefits shown in Tables 2-17 and 2-18, expressed in billions of dollars. The benefit in each category is smaller than using a cost-of-borrowing discount rate because future benefits are more heavily discounted. The aggregate benefits are much smaller ($7.2 billion rather than $15.5 billion and $101.9 billion rather than $157.9 billion respectively), but even at the higher discount rate, natural hazard mitigation still appears to be cost-effective in every category.

Consider the total for 1 year of designing to exceed 2015 I-Code requirements and to comply with the 2015 IWUIC. New construction would save approximately $2 in avoided future losses for every $1 spent on additional, up-front construction cost. Now consider the subtotal for the past 23 years of federally funded natural hazard mitigation. At a 7% discount rate, society saved approximately $4 for every $1 spent.

Mitigation category	Cost (billions)	Benefit (billions)	BCR
Exceed 2015 I-Code requirements for riverine flood	$ 0.91	$ 2.28	3
Exceed 2015 I-Code requirements for hurricane surge	$ 0.01	$ 0.03	3
Exceed 2015 I-Code requirements for hurricane wind	$ 0.72	$ 1.47	2
Exceed 2015 I-Code requirements for earthquake	$ 1.20	$ 2.16	2
Comply with 2015 IWUIC	$ 0.80	$ 1.26	2
Total, 1 year of exceeding 2015 I-Codes	**$ 3.6**	**$ 7.2**	**2**

Table 2-17. Total cost, benefit, and BCR of exceeding 2015 I-Codes using a 7% discount rate.

Mitigation category	Cost (billions)	Benefit (billions)	BCR
Grants for riverine flood	$ 11.50	$ 33.81	3
Grants for wind	$ 13.60	$ 65.10	5
Grants for earthquake	$ 2.20	$ 2.88	1.3
Grants for fire at WUI	$ 0.06	$ 0.07	1.3
Total, 23 years of grants	**$ 27.4**	**$ 101.9**	**4**

Table 2-18. Total cost, benefit, and BCR of federal mitigation using a 7% discount rate.

2.10 Job Creation for Designing to Exceed 2015 I-Code Requirements

The $3.6 billion 1-year increase in construction expenses would add 1% to current annual construction costs. Applying Equation 4-35 to all perils (flood, wind, earthquake, and WUI fire), The project team estimated that new design to exceed 2015 I-Code requirements would add approximately 87,000 jobs to the construction-material industry.

This Interim Study estimated that U.S. construction costs would rise by $3.6 billion annually if everywhere it were cost-effective to do so, people built new buildings to exceed 2015 I-Code requirements for flood, wind, and earthquake, and likewise complied with the 2015 IWUIC everywhere with a BCR greater than 1.0 (Table 2-11).

On an expected-value basis, those added costs would eventually be more than offset by reduced future losses. In the interim, the added construction costs would lead to an increase in employment, by about 8.65 million domestic jobs times the ratio of added construction cost to current annual construction cost. The project team elsewhere estimated that new construction adds or replaces about 1% of existing construction each year, which, as of 2016, totaled approximately $36.2 trillion (Porter, unpublished), or approximately $362 billion in annual new construction. (Not purchase price, just the replacement cost of the buildings.) The project team did not attempt to quantify job creation for federally funded natural hazard mitigation to existing buildings. See Section 4.22 for a discussion on how the project team calculated job creation.

2.11 Avoided Deaths, Injuries, and Cases of PTSD

The project team estimated that new buildings designed to exceed 2015 I-Code requirements and to comply with the 2015 IWUIC would avoid deaths, nonfatal injuries, and incidents of PTSD that by U.S. government standards would be worth spending $2.0 billion. Considering the relative rates of deaths and injuries in applying above-code measures for earthquake, that $2 billion equates with preventing approximately 32,000 nonfatal injuries, 20 deaths, and 100 cases of PTSD.

The past 23 years of federally funded natural hazard mitigation is estimated to prevent deaths, nonfatal injuries, and PTSD worth $68 billion, equivalent to approximately 1 million nonfatal injuries, 600 deaths, and 4,000 cases of PTSD. (See Section 4.17 for more details on the calculation of injuries, deaths and PTSD.)

Box 2-3. Natural-Hazard Mitigation Saves Lives

The past 23 years of mitigation provide the majority of the estimated savings in deaths, nonfatal injuries, and PTSD, compared with 1 year of designing to exceed 2015 I-Code requirements, probably because (a) past grants have focused on mitigating the most-risky existing buildings, and (b) current I-Codes do a very good job of protecting life. However, both kinds of mitigation do save lives. Together, they will prevent an estimated 620 deaths, 1 million injuries, and 4,100 cases of PTSD. The BCRs presented here already reflect the enhanced life safety using U.S. government figures of the acceptable cost to avoid future statistical deaths and injuries, but it seems worthwhile to remember that the safety benefits across these mitigation strategies reflect the safety of more than 1 million people and their families who will be able to continue their lives after a natural disaster because foresighted individuals, communities, and governments took action and invested money to protect them before disaster struck

Evaluating Reasonableness of the Results. The U.S. National Center for Health Statistics estimated that floods and storms killed approximately 475 people in the United States in the years 2006 through 2010 inclusive (Berko et al. 2014), or about 100 per year. Because this period does not include 2005, in which Hurricane Katrina killed between 1,200 and 1,800 people, the longer-term average might be closer to 200 per year. Compare these statistics with avoiding 20 deaths per year from designing to exceed 2015 I-Code requirements and about 30 avoided deaths per year from federal grants for natural hazard mitigation the fatality estimates seem reasonable on an order-of-magnitude basis.

It is harder to validate the estimated number of nonfatal injuries, since the estimates include the vast majority (perhaps 9 out of 10) that do not require treatment in a hospital, either because they are self-treated or treated by medical professionals outside of a hospital. Approximately 1,600 nonfatal injuries and instances of PTSD occur per disaster-related fatality. In the 1994 Northridge Earthquake, Seligson and Shoaf (2003) estimated that approximately 250 nonfatal injuries required medical attention in a hospital for each death, 500 nonfatal injuries were treated by medical personnel outside of a hospital for each fatality, and nearly 7,000 people self-treated injuries per fatality. The figure estimated here—1,600 injuries per death—lies within the range of injuries per death suggested by Seligson and Shoaf.

2.12 Savings to the Federal Treasury

The 2005 *Mitigation Saves* study estimated the savings to the federal treasury that resulted from FEMA funded natural hazard mitigation. The estimate resulted from multiplying recent federal expenses by the ratio of average annual property damage and casualty reduction to average annual property damage and casualty reduction in the United States. In the 2005 study, the project team estimated the ratio to be approximately 0.17. In the *2017 Interim Report*, the ratio appears to be 0.080, based on the quantities shown in Table 2-19. Using essentially the same methodology as the 2005 *Mitigation Saves* study, the project team estimated that the natural hazard mitigation efforts ultimately save the federal treasury $850 million annually, as detailed in Table 2-20. That figure is smaller than the $970 million figure estimated in 2005 (about $1.3 billion in 2016 USD) because savings are estimated using a factor that has in its denominator the total annual costs of natural hazards. The figure has risen greatly since 2005. Despite the increase, annual federal expenditures have risen since 2005 (about $6.6 billion in 2016 USD, versus $9.2 billion today—an increase of 40%) and the estimate of the factor *f* is lower by about half.

Quantity	Billions
Total benefit *B* calculated in this Interim Study	
Above code measures	$ 15.45
Federal mitigation grants	$145.87
Total benefit *B* from natural hazard mitigation	$161.32
ΔEAL: convert benefit *B* to annuity at approx. 2.2%, 75 yr	
Above code measures	$ 0.42
Federal mitigation grants	$ 4.28
Total ΔEAL from natural hazard mitigation	$ 4.70
Average annual cost of natural disasters, 3 sample years	
2011[(a)]	
2011 money	$ 16.00
2011 deaths	$ 5.00
2011 nonfatal injuries by approximate ratio with deaths[(b)]	$ 49.97
2011 total, billions, inflated to 2016 USD[(c)]	$ 81.94
2014	
2014 money only	$ 25.00
2014 add deaths and injuries by approximate ratio	$ 7.50
2014 total, billions, inflated to 2016 USD[(c)]	$ 34.25
2016	
2016 money[(e)]	$ 46.00
2016 deaths[(e)]	$ 1.31
2016 nonfatal injuries by approximate ratio	$ 12.66
2016 total	$ 59.97
Average of 3 years	$ 58.72
Factor *f*: ratio of ΔEAL to average annual cost of natural disasters	0.08

(a) Based on numerous sources including NOAA (2017b)
(b) About $10 nonfatal injuries per $1 fatal injuries
(c) Inflated using GDP deflator (World Bank per-capita GDP, PPP, international dollars)
(d) *New York Times* (https://www.nytimes.com/interactive/2015/08/04/upshot/regional-natural-disasters.html)
(e) *Insurance Journal* (https://www.insurancejournal.com/news/national/2017/01/10/438452.htm)

Table 2-19. Factor *f* used to estimate savings to the Federal Treasury.

Category of Federal Government Expenditures Saved	Quantity (base year $ million)	Year	Quantity (2016 $ million)	*f*	Savings (2016 $ million)	Source of base data
Public assistance	$5,229	2013	$ 5,698	0.080	$ 456	FEMA (2013d)
Individual assistance/human services	$1,400	2015	$ 1,434	0.080	$ 115	GAO (2014)
Mission assignments /standby grants	$ 44	2016	$ 44	0.080	$ 4	FEMA (2016b) Table 5 Readiness support contracts and interagency agreements
FEMA administrative costs	$ 442	2016	$ 442	0.080	$ 35	FEMA (2017a)
Mitigation grants and contracts	$ 387	2013	$ 421	0.080	$ 34	FEMA (2013d)
U.S. Small Business Administration default and administrative costs	$1,032	2014	$1,087	0.080	$ 87	SBA (2012-16)
U.S. Army Corps of Engineers emergency measures	$ 33	2016	$ 33	0.080	$ 3	USACE (2016) Fig. 2
Subtotal					$ 733	
Federal tax revenues recouped					$ 116	MMC (2005) Table 6-8, ratio of subtotals
Grand total					**$ 849**	

Table 2-20. Estimated annual savings to the Federal Treasury resulting from natural hazard mitigation.

2.13 Other Sensitivity Tests

2.13.1 Designing to Exceed 2015 I-Code Requirements for Coastal Flooding

The 2017 project team examined how several uncertain input variables affect the estimated BCR for designing to exceed 2015 I-Code requirements for coastal flooding in coastal V- and VE-zones. These inputs included: 1) sea level rise; 2) discount rates; 3) storm surge height; and 4) economic life of the building.

The team tested five sea-level-rise scenarios, selected from among those examined by NOAA (2017), in addition to one other scenario. Each scenario depicts a path in which global mean sea level (GMSL) will rise by the end of the 21st century—ranging between zero and 2.5 meters (about 8 feet). See Table 2-21. Scenario 3 represents a baseline assumption.

Scenario	1	2	3 (baseline)	4	5
NOAA (2017) label	(N/A)	Low	Int-low	Int-high	Extreme
GMSL rise by 2100 (m)	0.0	0.3	0.5	1.5	2.5
BCR (BCR)	6.4	7.0	7.3	8.4	9.1

Table 2-21. Sensitivity of the BCR for greater elevation of new coastal buildings to sea level rise (Low, Intermediate-low, intermediate-high, and extreme.).

The table shows that while sea level rise influences the BCR for building coastal buildings higher above BFE, the measure can be highly cost-effective regardless of the degree of sea level rise.

Additional sensitivity tests. The project team also varied the discount rates, the economic life of the building, and the wave height, examining how each uncertain input affects the BCR. The team considered four discount rates: (1) baseline (cost-of-borrowing, approximately 2.2%), (2) OMB required value of 3%, (3) OMB required value 7%, and (4) no discounting. The project team tested sensitivity of BCR to the economic life of a new building: the baseline 75 years, plus two additional scenarios that adjust the economic life of the building by ±15 years. Finally, wave height is uncertain. NOAA's MOM wave heights used for this analysis are discussed at length in section 4.10.2. Although these are scaled using FEMA FIS, they represent not only an independent view, but a source of uncertainty. The project team adjusted the wave heights by ±25% at all locations, for all storm categories. Table 2-22 presents the results.

	Baseline	Discount rate			Economic life		Wave height	
		0%	3%	7%	60 years	90 years	-25%	+25%
BCR	7.3	13.9	6.0	3.4	6.5	7.8	5.3	9.1

Table 2-22. Sensitivity of the BCR for greater elevation of new coastal buildings to other input variables.

The table shows that regardless of uncertainty in these input variables, it is cost-effective to design new coastal buildings higher above BFE than the 2015 I-Codes require. The BCR is most sensitive to wave height and discount rate, both with a range of approximately 3.8 (ignoring the 0% option discount rate). A reasonable domain of economic life produces a range of about 1.3.

2.13.2 Designing to Exceed 2015 I-Code Requirements for Hurricane Wind

The project team tested how strongly various uncertain inputs affect the BCR of compliance with the IBHS FORTIFIED Home Hurricane Program. The project team varied three key parameters, each time keeping the others at their baseline value: 1) discount rate; 2) economic life of the building; and 3) design wind speeds. The analysis was conducted for discount rates of 0%, 3% and 7% (as opposed to approximately 2.2%, which was used as the baseline), for a 50-year and 100-year building life (as opposed to 75 years) and design wind speeds of ± 5 mph of those listed in ASCE 7-16 (ASCE/SEI 2016). Table 2-23 shows how the BCR for the IEMax uptake of IBHS FORTIFIED Home Hurricane varies with three important inputs. Figure 2-24 illustrates the table.

	Baseline	Discount rate			Economic life		Wind speed	
		0%	**3%**	**7%**	**50 years**	**100 years**	**-5 mph**	**+5 mph**
BCR	5.3	10.6	6.6	2.2	4.4	5.8	3.5	8.0

Table 2-23. Sensitivity of BCR for adopting IBHS FORTIFIED Home Hurricane to three important inputs.

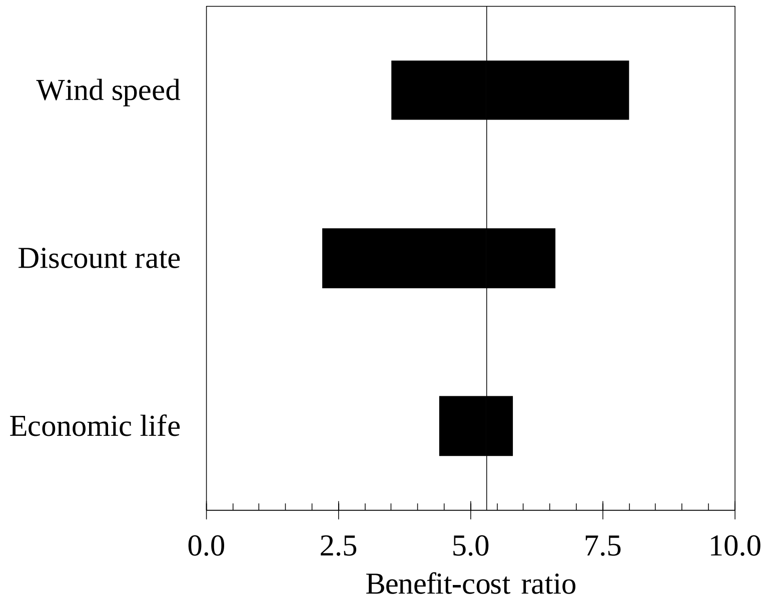

Figure 2-24. Sensitivity of BCR for designing to exceed 2015 I-Code requirements for wind to major uncertain variables.

Table 2-23 and Figure 2-24 both show that regardless of uncertainty in important inputs, designing to exceed 2015 I-Code requirements for hurricane wind using IBHS FORTIFIED Home Hurricane can be cost-effective, even with a very high discount rate of 7%. The fact that the BCR shows little sensitivity to uncertainty in the economic life of a new home (varying about ±15% for a ±33% change in economic life) reflects the fact that the last 25 years of economic life are the most discounted—they matter much less than the first 25 years. As for wind speed, the table shows that BCR is sensitive (varying by a factor of 1.5 either way) to where a house lies within a 10-mph wind speed band. In ASCE 7-16, a 10-mph band of basic wind speed (the wind speed with 700-year mean recurrence interval) is about the width of a typical coastal county, which implies that two identical houses, one on the Gulf or Atlantic Coast and the other at the far inland end of the county, will experience substantially different benefits from designing to exceed 2015 I-Code requirements.

2.13.3 Designing to Exceed 2015 I-Code Requirements for Earthquake

Benefits and costs of designing to exceed 2015 I-Code requirements for earthquake depend on more than how much the designer increases strength and stiffness. They also depend on the added cost of construction, building economic design life, building replacement cost, and several intermediate parameters of the vulnerability functions, which one might approximate with an overall multiplier on vulnerability. The project team tested the sensitivity of the BCR to these uncertain parameters using the values shown in Table 2-24. In most cases the project team chose high and low values by judgment. The table shows the baseline benefit, cost, and BCR on the first row, then the benefit, cost, and BCR for each what-if condition. The table includes the effects of varying discount rate, for completeness.

Parameter	Value	Benefit ($ billion)	Cost ($ billion)	BCR
Baseline				
		4.37	1.23	3.6
Discount rate				
Baseline	Varies			
OMB low	3%	3.59	1.13	3.2
OMB high	7%	1.83	0.79	2.3
Economic life (years)				
Baseline	75			
Short	50	3.50	1.24	2.8
Long	100	3.38	1.10	3.1
Replacement cost (multiple of baseline value)				
Baseline	1.00			
Low	0.67	3.84	1.19	3.2
High	1.50	5.25	1.32	4.0
Vulnerability (multiple of baseline value)				
Baseline	1.00			
Low	0.67	2.74	0.99	2.8
High	1.50	7.30	1.86	3.9
Construction cost to exceed 2015 I-Code earthquake requirements (x baseline)				
Baseline	1.00			
Low	0.67	4.86	1.23	3.9
High	1.50	4.09	1.48	2.8

Table 2-24. Sensitivity of BCR for designing to exceed 2015 I-Code earthquake requirements to various uncertain parameters.

The table shows that designing to exceed 2015 I-Code earthquake requirements is always cost-effective for some fraction of the buildings built in 1 year (see the column labeled “cost”). It is always ±25% of the baseline, meaning that in every scenario, designing to exceed 2015 I-Code requirements for earthquake would make sense on a BCR basis for 20 to 30% of the building stock. In each case, the overall nationwide average BCR varies within -50% to +10% of the baseline value. The table is illustrated in Figure 2-25, which sorts the uncertain input parameters (each corresponding to one of the horizontal bars) in decreasing order from top to bottom of the range of BCRs. The x-values of the ends of the bars correspond to the minimum and maximum BCRs resulting from varying that input. In some cases, one end of the bar corresponds to the baseline input, e.g., discount rate, where the baseline is less than either of the two values used by OMB.

All the values seem reasonable relative to the baseline. Higher discount rates should generally reduce cost-effectiveness, because benefits accrue for reduction in future losses, and the less one values future dollars, the less the benefit. A longer economic life should increase cost-effectiveness, since benefits accrue for a longer period of time. More value exposed to loss should generally increase the BCR. Similarly, greater vulnerability should generally increase the BCR, because more strength and stiffness will make a bigger difference in future losses. In addition, higher construction cost for designing to exceed 2015 I-Code requirements should generally decrease cost-effectiveness.

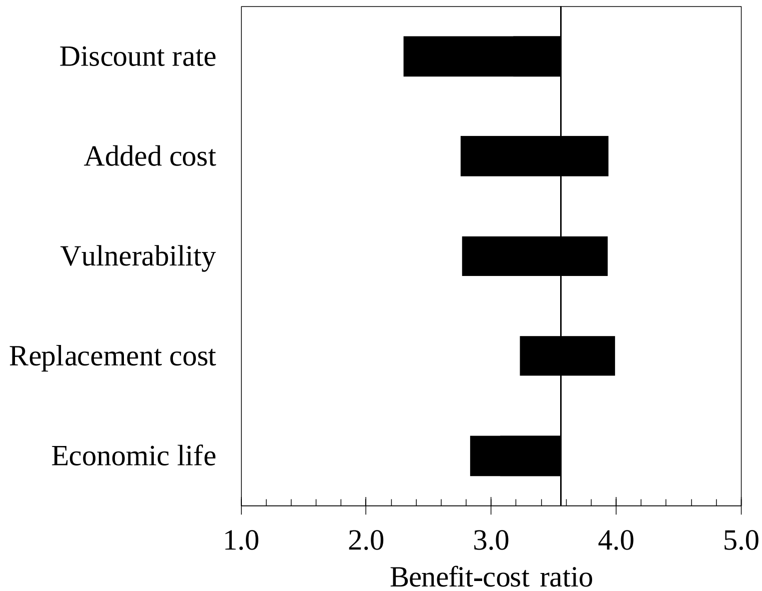

Figure 2-25. Diagram of sensitivity analysis of BCR for designing to exceed 2015 I-Code requirements for earthquake.

2.13.4 Designing to Comply with 2015 IWUIC

Figure 2-26 shows the sensitivity of the results for complying with the IWUIC to various inputs, where key inputs were varied ±33%. Results are most affected by increases in BP or flame intensity level (e.g., the hazard) and the cost (e.g., value) of the house, all of which directly increase mitigation benefits. Increasing the cost of structural compliance is the next most-significant variable driving up overall cost and decreasing the BCR, as does an increase in interest rates (which drives up the cost of future vegetation management). The cost of mortality has a negligible effect: between 1990 and 2012, firefighter and civilian fatalities associated with wildland fire averaged between 10 to 20 and 5 to10 per annum, respectively (IAWF 2013). Very few of these occurred with structures, so the reduction of fatalities that would result from complying with the 2015 IWUIC, while accounted for, translated into a negligibly small dollar amount. The cost of PTSD is more significant. While negligibly few are killed, everyone suffers stress if their home is under threat, or destroyed, by fire. The cost of PTSD is significant, although still not widely recognized.

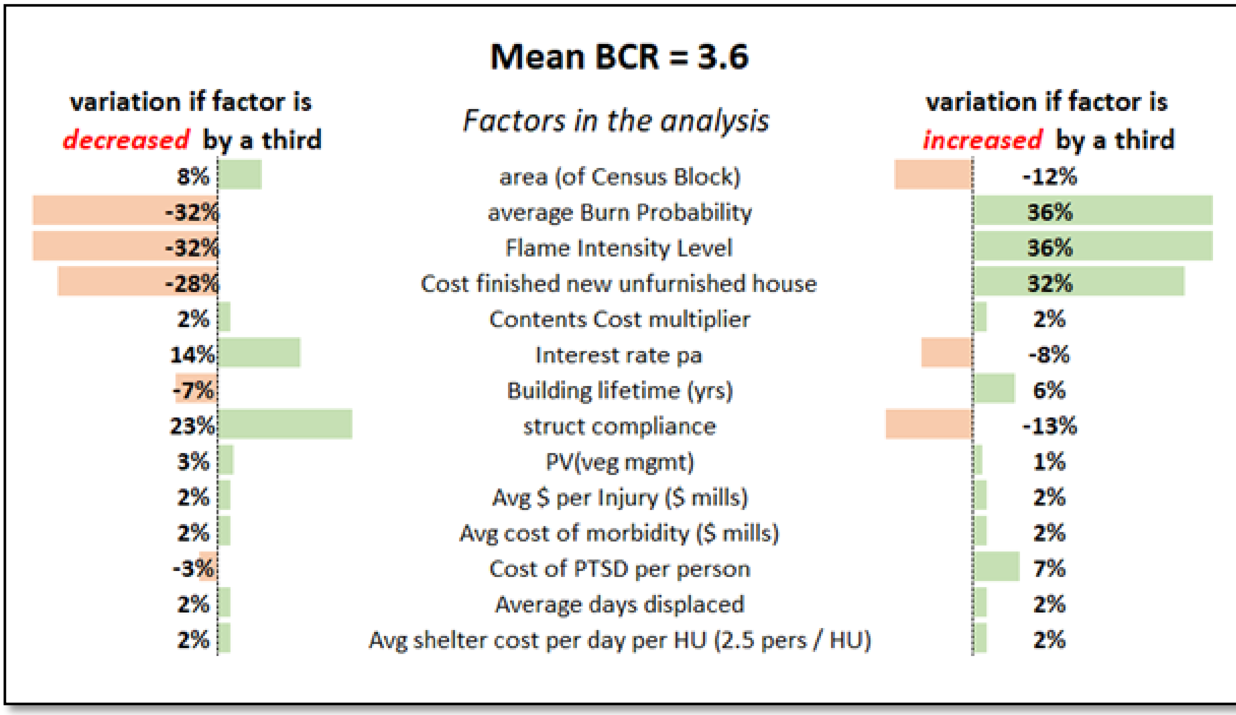

Figure 2-26. Sensitivity tests for compliance with 2015 IWUIC.

2.13.5 Federal Grants

In light of the findings that (1) designing to exceed 2015 I-Code requirements is cost-effective regardless of reasonable values of the input variables, (2) the 2005 *Mitigation Saves* study found similar results for federally funded natural hazard mitigation, and (3) BCRs for federal mitigation grants work are similar to, and somewhat higher than, those calculated in the 2005 *Mitigation Saves* study, it seems unnecessary for the project team to perform additional sensitivity analyses of federal mitigation grants work for the ongoing study.

3 Review of Mitigation Guidance and Quantification of Benefits

3.1 Building on Prior Work

While the 2005 *Mitigation Saves* study is a widely recognized study of mitigation measures and their benefit-cost ratios (BCRs), it is not the only such work. In preparation of the expanded 2017 study, the project team identified and reviewed relevant literature on building codes and standards (including guidance on going above such codes), methods to quantify disaster-related losses, and prior efforts to determine BCRs.

3.2 Relevant Building Codes and Standards

Most communities in the United States require new buildings to comply with requirements of the IBC (ICC 2015a) or IRC (ICC 2015b). The IRC attempts through prescriptive methods to achieve approximately the same level of performance as the IBC does through engineering calculations (see ICC 2015b pg. vii).

To specify minimum design loads for wind, earthquake, and flood, the IBC adopts ASCE/SEI 7 by reference (ASCE, 2010). This standard also specifies the most widely accepted standard procedures in the United States for characterizing site conditions such as soil (for earthquake loading) and surface roughness (for wind loading) and for estimating one aspect of hazard as a function of another, such as ground motion on one soil type given ground motion on another.

ASCE/SEI 7 does not address fire at all, excepting seismic requirements for fire sprinklers and fire protection of seismic isolation. The IBC addresses fire protection, though not fire at the WUI. Instead, the ICC offers the IWUIC (ICC 2015c). The IWUIC establishes “minimum standards to locate, design and construct buildings and structures or portions thereof for the protection of life and property, to resist damage from wildfires, and to mitigate building and structure fires from spreading to wildland fuels.” The IWUIC addresses access (especially for firefighting), water supply, ignition-resistant construction and materials, and defensible space (meaning the continuous maintenance of a largely flammable-free zone within 30 to 100 feet of a building for the life of the building).

3.3 Options to Exceed Code Minimum Requirements

3.3.1 Options to Exceed Minimum Wind Design Requirements

The project team identified multiple options to make a new building more resistant to wind loads than current codes require.

Safe room. According to the introductory webpage for *FEMA P-320 - Taking Shelter from the Storm: Building a Safe Room for Your Home or Small Business* (FEMA 2014f), “Having a safe room in your home or small business can help provide near-absolute protection for you and your family or employees from injury or death caused by the dangerous forces of extreme winds. Near-absolute protection means that, based on our current knowledge of tornadoes and hurricanes, the occupants of a safe room built according to the guidance in this publication will have a high probability of being protected from injury or death. Our knowledge of tornadoes and hurricanes is based on numerous meteorological records as well as extensive investigations of damage to structures from extreme winds. Having a safe room can also relieve some of the anxiety created by the threat of an oncoming tornado or hurricane."

FEMA P-361 - *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms* Chapter A-3 offers cost estimates for adding safe rooms to new buildings, and some guidance for performing a BCA. For example, its authors estimate that to "design and construct a portion of a new building to resist 250-mph winds from a 140-mph basic wind speed" would add 5% to 7% to the construction cost of the building. The cost is "associated primarily with additional cost of structural elements and envelope opening protection."

City of Moore Code Enhancements. In 2014 the City of Moore, Oklahoma, after experiencing a third deadly tornado in 15 years, adopted enhancements to the 2009 IRC that effectively increased design wind speeds from 90 mph to 135 mph and added 12 detailing requirements (City of Moore, 2014a and Ramseyer and Holliday, 2014). See City of Moore Municipal Code, Part 5, Chapter 2, Article A Section 5-204.C as of June 18, 2014 for the city's modifications to the 2009 IRC (City of Moore 2014b). They are also duplicated in Appendix C of this Interim Study.

IBHS FORTIFIED Home. The Insurance Institute for Business & Home Safety (IBHS) offers a suite of design standards labeled "FORTIFIED Home" that aims to better protect existing and new buildings from hurricanes, hail, and high winds relative to the minimum requirements of the IRC.[7] Each of its three new-building standards, FORTIFIED Home Hurricane Standards (IBHS 2012), FORTIFIED Home High Wind and Hail Standards (IBHS 2015a) and FORTIFIED Home High Wind Standards (IBHS 2015b) provide three optional levels to exceed I-Code design requirements. Each set of standards has a bronze, silver, and gold designation, with silver aiming for generally greater protection than bronze, and gold better than silver. The gold hurricane designation, for example, aims to "minimize damage and loss resulting from a [Saffir-Simpson Hurricane Wind Scale (SSHWS)] Category 3 hurricane." FORTIFIED Homes involve the following enhancements:

1. Improve roof sheathing attachment and roof deck sealing (bronze, silver, and gold)
2. Sheath gable end walls, if necessary (bronze, silver, and gold)
3. Improve the attachment of outlookers at gable ends (bronze, silver, and gold)
4. Reduce chances of attic ventilation system failure (bronze, silver, and gold)
5. Protect all openings (glazed openings, entry doors, and garage doors) (silver and gold)
6. Strengthen gable ends over 4 feet in height (silver and gold)
7. Improve the anchorage of attached structures (porches and carports) (silver and gold)
8. Provide a continuous uplift connection between roof support members, exterior bearing walls, multi-story floors, down to the foundation (gold only)
9. Adequately secure chimneys to the structure (gold only)

[7] Note that in some locations, state and local requirements exceed those of the IRC, such as those adopted after Hurricane Andrew in Florida's Miami-Dade or Broward Counties. The authors do not consider these local differences from the IRC, and do not calculate the BCR of exceeding them.

10. Ensure that windows and doors meet appropriate design pressures in addition to being protected from windborne debris (gold only)

IBHS has begun development of a standard to address high winds in the Central United States that covers a basic windspeed of 140 mph in ASCE/SEI 7-10 Exposure Category B, which comprises most buildings in urban and suburban areas. (The IBC's basic windspeed for Risk Category II—most buildings—in most of the central United States is Exposure Category C is 115 mph. That basic windspeed is estimated to have a 7% exceedance probability in 50 years.) The IBHS standards and the American Wood Council's (2015) *Wood Frame Construction Manual* for 140 mph exposure B include prescriptive load path requirements that are similar to those recently adopted in the Moore, Oklahoma Municipal Code and that appear in Appendix Y of the *Oklahoma Uniform Building Code* (Oklahoma Uniform Building Code Commission 2016).

3.3.2 Options to Exceed Minimum Flood Design Requirements

The most recognized organized effort to mitigate flood damage to buildings in the United States is FEMA's NFIP. The NFIP insures property from flood damage and promotes flood risk mitigation strategies. In voluntarily participating communities (counties, municipalities, and tribal nations), buildings that are newly constructed, significantly improved, or significantly repaired must comply with NFIP standards. Communities also have the option to adopt the IBC, IRC, and the IECB (ICC 2015d).

While acquisition is identified as the most effective mitigation strategy in terms of eliminating residual risk to the structure and ongoing risk to emergency responders (ASFPM 2014), one of the main flood-mitigation strategies in the NFIP regulations and I-Codes is that buildings in the riskiest flood zones be elevated 1 foot above the height of water expected in the 1% annual chance flood zone, known as the base flood elevation (BFE). Such elevation above BFE also is called freeboard. Additional requirements exist for adding freeboard for critical facilities depending on the type of facility and flood zone (ICC 2014, FEMA 2013b). Communities that use I-Codes have the option to establish a design flood elevation (DFE) that exceeds I-Code standards (ICC 2014).

In addition, FEMA offers design standards for other modifications to reduce flood damage (FEMA 2015a, b). Options include dry floodproofing to prevent water from entering buildings; elevating sensitive equipment to be less likely to experience flooding; and designing lower levels to allow flooding without damage. Walls or levees offer yet another option.

According to NFIP regulations, flood damage-resistant materials must be used for construction below the BFE. Flood-resistant materials are able to withstand at least 72 hours of flooding without sustaining significant damage (FEMA 2008b). There are five classifications of flood damage materials, and only class 4 and 5 materials can be used below the BFE in the special flood hazard area (SFHA).

A 2014 nationwide study found that NFIP floodplain management practices avoid $1.87 billion in damages annually (FEMA 2014a). Including model building codes as part of the NFIP would further reduce losses from flood and other hazards and also benefit land use planning (FEMA 2013c). The most significant benefit of implementing building codes would likely come from elevating buildings located in flood zones. Multiple FEMA studies (2014a, 2014b, 2013c, 2008a, Jones et al. 2006) have found that adding freeboard is one of the most effective ways to reduce losses in the most hazardous flood zones. Since NFIP standards have been implemented, hundreds of thousands of buildings have been built to its minimum requirements, while relatively few have included extra freeboard (FEMA 2013c).

Over 22,000 communities participate in the NFIP (FEMA 2016a). Approximately 70% of NFIP communities already use I-Codes (FEMA 2013c). Twenty-two states have already fully adopted and mandated I-Codes at the state and local levels, so national inclusion of building codes in NFIP would have little effect on them (FEMA 2013c). Most of the states with mandatory enforcement are on the east and west coasts. In the remaining 28 states, 87% of communities that are in the SFHA participate in the NFIP, but only 20% of them enforce I-Codes. If I-Codes became a requirement at the federal or state level, these states would need additional resources to administer the building codes, train personnel to do so, and support increased coordination between state, local, and federal agencies. Implementing I-Codes in the NFIP would initially increase costs in areas that do not already use them, but in the long term, implementation would increase property values, reduce hazard losses, reduce insurance rates, and improve the financial stability of the NFIP (FEMA 2013c). Rural communities may have fewer resources and need more third-party options for code enforcement, but the benefits are similar to those in urban communities (FEMA 2013c, White House 2016).

Data from the NFIP's Community Rating System (CRS) can be used to identify communities that have additional elevation requirements in states that do not enforce a statewide building code. Such communities are most common in the southeastern (especially Florida) and the western United States, along with a few communities in the Midwest and Northeast (FEMA 2014b).

Elevating a residential building typically costs tens of thousands of dollars, and adding freeboard might add approximately 1% of the total construction cost per foot of elevation, although flood insurance premium discounts can offset the costs of additional freeboard within a few years (FEMA 2013c, 2008a). Note that insurance premium discounts can be complex and nuanced when pre-flood insurance rate map (FIRM) and post-FIRM rates are taken into account. A report for FEMA (2008a) found that 1 to 2 feet of additional freeboard was almost always cost-effective for the 1% annual chance flood, and three to four feet was cost-effective in some situations. Adding 1 to 2 feet of freeboard also earns a larger reduction on NFIP premiums. Adding 3 to 4 feet does not earn a major reduction compared to 2 feet (FEMA 2010). Additional freeboard can also mitigate against risk associated with error or uncertainty in flood risk maps and risk associated with climate change, making buildings more likely to withstand a particularly severe flood. FEMA pilot studies have indicated that 1 to 2 feet of additional freeboard could save a medium-size city, such as Charleston, South Carolina, tens of millions of dollars and save over $10 billion across FEMA Region IV (the southeastern United States) if the entire region experienced the 1% annual chance flood. In FEMA Region IV, 42% of buildings already had freeboard (FEMA 2014b). Table 3-1 recaps the foregoing options.

Option	Cost	Damage reduction	Measure Lifetime
Building elevation or fill basement	Moderate to high	High	30-50 years
Flood openings	Low	High	15-20 years
Elevate utilities	Low to moderate	Moderate	15-20 years
Flood wall or levee	High	Moderate	50-100 years
Dry floodproofing	High	Moderate	15-30 years
Flood-resistant building materials	Moderate	Limited	10-20 years

Table 3-1. Flood damage mitigation strategies and general cost-effectiveness, based on FEMA (2015).

Some developers are already implementing additional elevation as one of the key strategies for mitigating future flooding impacts. The area in and around Long Island, NY offers many examples where developers are choosing to exceed state and local requirements by including additional elevation to protect their investments from future flooding. For example, on an East Rockway waterfront property previously occupied by a marina destroyed in Hurricane Sandy, the Beechwood Organization is elevating 84 new condominiums over parking, placing all mechanical equipment on roofs, and other similar measures. The additional efforts that exceed state requirements cost approximately $5 million. Likewise, in Glen Cove, RXR Realty is raising the ground level of a 56-acre waterfront development, Garvies Point, by 6 to 10 feet. In its Shipyard project in Port Jefferson, the Tritec Real Estate Company is elevating the 112 apartments over a parking garage and installing drainage pumps in the garage, even though the waterfront complex is located outside the designated flood plain. In downtown Riverhead, the Community Development Corporation of Long Island and Conifer Realty are building 45 apartments that will be on the second floor or higher to protect them from floods. The electrical systems will be at least 2 feet above the height of 1% annual chance flooding (McDermott 2017).

Besides increasing elevation, flood openings are the only strategy that can be implemented at the single-building level that FEMA (2015a) has estimated to have a high potential to reduce damage. Flood openings can be used to meet IBC requirements. They not only have a lower cost than elevation but also have a lower expected lifetime. Filling in basements, abandoning a lower floor, and elevating the lowest interior floor all have similar costs to building elevation, although these measures may not meet all codes. Using flood-resistant materials has limited potential to reduce damage. Construction of walls or levees around a building is a high-cost, long-lasting measure that may be effective in reducing damages (FEMA 2015a). However, there are limits on how high walls and levees can be. They may not be high enough to prevent damage, and they must be maintained. Also, nearby terrain and geotechnical conditions may make walls and levees impractical.

In light of the advantages and disadvantages of the options considered here, additional freeboard seems to warrant the most attention for the portion of this Interim Study concerned with exceeding minimum flood design requirements.

3.3.3 Options to Exceed Minimum Earthquake Design Requirements

Option 1: Adopt I-Codes where no code is currently required. Communities that do not adopt or enforce the IBC and IRC, or who adopt them but weaken the disaster-resistant aspects, could adopt the I-Codes without weakening the disaster-resistant aspects, and enjoy the benefits of the mitigation already provided by those codes. There are jurisdictions across the United States that do not adopt the I-Codes in full, including those in the central and eastern United States where seismic risk is less widely appreciated. The lack of modern building codes with seismic code provisions intact in those places poses a particularly acute problem. Furthermore, adoption and enforcement of modern building codes is not a one-time process. It must be continuously maintained. Many jurisdictions across the United States face budgetary challenges. Building codes and building departments are often threatened with pressure to lower costs to promote development. The pressure threatens a building code system funded to support modern adoption and enforcement of codes and training. Option 1 therefore offers the advantage of widespread relevance, simplicity, and authoritativeness. The option suffers from a disadvantage however: the analysis would be largely irrelevant to U.S. communities where I-Codes are already adopted and to many communities where designing to exceed minimum earthquake design requirements might be most valuable. However, this option is important enough to address as a standalone effort under the next phase of this project.

Option 2: Stronger. Porter (2016a) explores an option for seismic design beyond life safety: designing all new buildings with a seismic importance factor of 1.5, e.g., making them 50% stronger than ordinary buildings are required to be under the requirements of the 2015 IBC. Making buildings stronger makes them less likely to collapse. One could make new buildings stronger than ASCE/SEI 7-10 requirements by a factor of 1.25, 1.5, or some other higher value, depending on material, location, and other considerations. For example, there is evidence from the Consortium of Universities for Research in Earthquake Engineering (CUREE)-CalTech Woodframe Project (Porter et al. 2006), that stronger design can be cost-effective, especially near large active faults.

Some entities routinely require new buildings to be stronger than code requirements, such as CalTech had for three decades. CalTech dropped the use of a 1.5 importance factor around 1997. CalTech Design and Construction (2014) justified the change based on improvements in the 1997 Uniform Building Code. A CalTtch professor explained, “The building code caught up with what we were doing. The newer designs seemed strong enough (we require pushover curves), so the emphasis shifted to other things such as shearwall layout and using improved technology such as non-buckling braces.” (J. Hall, written communication, 24 Oct 2017.) At least two consulting clients of project team members also required some new buildings that they build and occupy to exceed code-minimum strength requirements.

Some readers may object that strength and stiffness generally go together, or that it is rarely possible to make a building 50% stronger without also making it stiffer. Reinforced concrete and reinforced masonry shearwall buildings largely derive their shear strength from steel reinforcing and their stiffness from concrete or mortar. One can add steel to increase their strength without significantly increasing stiffness. Such buildings are common throughout the United States. Similarly, the strength of woodframe buildings is commonly limited by connectors and their stiffness commonly controlled by sheathing. Strength and stiffness do not increase in proportion to each other in these common building types.

Option 3: Stronger and Stiffer. As a closely related alternative to strength, engineers could design new buildings to be both stronger and stiffer than ASCE/SEI 7-10 requires, by a common factor. For example, engineers could design a new building to resist shaking of 1.25 times what ASCE/SEI 7-10 requires, and to be commensurately stiffer as well. (More precisely, to deflect less at design-level shaking.) One could set the requirement at 1.25 times, 1.5 times, or some other value possibly as high as 5.0 or even higher, again depending on materials, location, etc. Compelling advantages of the strength-and-stiffness option include reducing collapse (and by extension red-tagging and yellow-tagging buildings) and reducing repair costs, since much of the costly (if not life-threatening) damage that buildings experience in earthquakes result from excessive deformation.

Again, the strength option would probably tend to produce greater stiffness, since providing greater strength tends also to provide greater stiffness, but the strength-and-stiffness option would ensure and control the increase in stiffness. Note that increasing stiffness can aggravate some aspects of damage, especially to acceleration-sensitive components, even as it reduces damage to the (generally more costly) drift-sensitive elements. Greater stiffness can also increase earthquake forces on the building, especially for mid- and high-rise buildings.

Option 4: Performance-based. A third option: engineers could design new buildings using performance-based earthquake engineering, for example using FEMA P-58 (FEMA 2012d). FEMA P-58 provides an analytical method to estimate building performance in terms of repair costs, life-safety impacts, and loss of function, and to iterate design to achieve the owner's performance goals. Engineers can finely tune the structural and nonstructural design. Except in cases of the simplest buildings, regular in both plan and elevation, a reasonably accurate FEMA P-58 analysis requires a nonlinear dynamic structural model. It is probably only practical for a modest subset of buildings: large ones built for owners who intend to occupy them for decades. It seems impractical to examine the BCR for FEMA P-58 in any kind of general way. It is building-specific and allows the designer to tailor hundreds or thousands of features to achieve any of a variety of performance objectives.

Other options. Additional options include various design features: base isolation (e.g., Mayes et al. 1990), supplemental energy dissipation (e.g., Constantinou et al. 1998), buckling-restrained braced frames (e.g., Sabelli et al. 2003 and NIST 2015), rocking structural systems, and energy-dissipating structural connections (e.g., Christopoulos et al. 2002). These all offer promise as techniques to reduce damage, but they are all somewhat specialized, applicable to one or a few classes of building, and not to the general building stock (GBS).

3.3.4 Complying with the IWUIC

Fire hazard exists in several different environments: urban, rural, and the contact between these two, which is called the WUI. Fire also aggravates other perils such as earthquakes, floods, and tropical cyclones. Historically, building codes have been dominated by urban fire risk reduction since the Great Fire of London in 1666, and enhancements continue to be made for the reduction of this hazard. Examples of historic code enhancements abound and are too numerous to detail here, but a few examples included requiring non-combustible roofing materials (whether outlawing thatched roofing in London after the Great Fire and in 18th Century Japanese cities, or outlawing wood shake roofs in Los Angeles in the 1970s), requiring fire stopping in U.S. woodframe buildings in the early 20th century, requiring panic bars and unlocked exits in U.S. public assembly buildings (as a result of the 1911 Triangle Shirtwaist fire in New York), and requiring enclosed stairways and sprinklers in high-rise buildings (the latter requirement still incomplete in many jurisdictions).

Moving to today, the WUI fire risk in the United States has only relatively recently become recognized as quite severe. The IWUIC (ICC 2015c) was first promulgated in 2003. Uptake has been sparse. Even though a large part of the country is at risk, only about 10% of the 70,000 communities in the United States at risk of wildland fire have yet to adopt the code (IAWF 2013). According to IAWF (2013), over 220 million acres (twice the area of California) have been designated as high-risk from WUI fire. These areas contain 46 million single-family homes, several hundred thousand businesses, and more than 120 million people (38% of the U.S. population). Furthermore, the potential for increased population within the WUI is large: only 14% of the available WUI lands in the western United States have been developed, leaving 86% available for development. Nationally those figures are 30% developed with 70% remaining to be developed. And the U.S. population is actually moving into the WUI. Since 1990, the United States has experienced an unprecedented conversion-growth rate of 3 acres per minute, 4,000 acres per day and close to 2 million acres per year of conversion from wildlands to WUI. Losses because of WUI fire are not merely theoretical. Over 38,000 homes have been lost since 2000, with financial loss of WUI fires in 2009 of approximately $14 billion. The costs for firefighting (not losses) exceed $4.7 billion per year, and many other loss costs are not generally accounted for (IAWF 2013).

The WUI fire situation differs from flood, earthquake or wind in that it has only been systematically addressed in the last few decades. In light of these observations, the project team chose to estimate the benefits and costs of complying with the 2015 IWUIC, rather than seeking to exceed it. It requires, generally, non-combustible roofing and fire-rated cladding, glazing, and underfloor protection; assurance of water supply; defensible space; and, in some places, residential sprinklers.

3.3.5 Options to Adopt or Better Enforce Minimum Design Requirements

Option 1 for earthquake (see section 3.3.3) applies more generally to other perils: a community that does not enforce recent I-Codes with their disaster-resistant features could do so, and better address flooding, windstorm, and other perils. A building owner or developer in one of those communities could build to comply with recent I-Codes despite not being required to do so. The word “recent” matters here. Model building codes with seismic design requirements have evolved greatly since their introduction in the United States with the 1927 *Uniform Building Code* (UBC), (International Conference of Building Officials, 1927). Beginning with the 1930 UBC and continuing through the 2015 IBC (ICC 2015), model codes have included generally-expanding mandatory requirements to resist both common loads and rare, extreme ones. Similar statements can be made regarding the evolution of the *Southern Standard Building Code* (Southern Building Code Congress International, 1946 et seq.) and BOCA *National Building Code* (Building Officials and Code Administrators International, Inc. 1950 et seq.).

Box 3-1. Mitigation Recently Incorporated into the I-Codes and Related Documents

Flood

2015 IBC: Refers to standards from *ASCE 24-Flood Resistant Design and Construction* and *FEMA Technical Bulletin 2* (2008b) on flood-resistant materials. Clarified determination of substantial damage and significant improvement.

2015 IRC: Requires 1 foot of additional elevation above BFE for Zones V, coastal A, and A. Clarified determination of substantial damage and significant improvement.

ASCE 24:
Uses Flood Design Class instead of Risk/Occupancy Class. Flood Design Class ranges from 1-4, with 4 being the most critical. There are different elevation requirements for different classes in different flood zones. Requires flood openings in zones V and coastal A for structures such as garages.

Wind

2015 IBC: New requirements for tornado shelters in certain buildings in areas where tornado shelter design wind speeds are 250 mph or greater. Clarifies special inspection requirements. Updated reference standard to ICC 500-2014 (ICC 2014a).

Seismic

2015 IBC: Seismic design maps for Guam and American Samoa. New diaphragm anchorage requirements. Clarifies special inspection requirements. Reference to 2013 edition of *ASCE 41-Seismic Rehabilitation of Existing Buildings* (ASCE 2013).

ASCE/SEI 7-10 3rd printing: New errata corrections, new commentary, and new supplement.

Fire at the WUI

2015 IWUIC: Requires non-combustible roof and rated cladding, glazing and underfloor protection, assured water supply, and defensible space (changes relative to 2003 edition).

The model codes have more or less continuously enhanced public safety and property protection, with occasional reductions to better balance reliability and economic efficiency. One could say that disaster resilience begins with building codes. It also seems likely that any effort to design in excess of code requirements would have a higher BCR the lower the baseline requirements. That is, if a new building is not required to meet the minimum requirements of the 2015 I-Codes, but elects to exceed them, the BCR is likely higher than if the 2015 I-Codes are required and a new building elects to exceed them.

It may be useful to review some recent enhancements. Box 3-1 summarizes enhancements made in the 2015 IBC relative to the 2012 edition. The rest of this section summarizes some recent research into the costs and benefits of meeting modern code requirements, relative to older codes or no codes.

The Insurance Services Office's (ISO) Building Code Effectiveness Grading Schedule (BCEGS) rates approximately 19,000 communities on adoption and quality of enforcement of building codes based on interviews (Wright et al. 2014). Insurers use it to assess how a community enforces its codes. CRS and BCEGS data show the connections between code adoption, enforcement, and losses.

Burby et al. (2000) examined the linkage between building code enforcement and construction activity in central cities. They showed that, "Central cities can capture a larger share of the market for single-family detached housing in their metropolitan areas and also spur commercial rehabilitation if they adopt more business-friendly approaches to building code enforcement. These gains can be achieved without reducing the degree of compliance with building regulations as long as enforcement efforts are strong. In short, one key to increasing economic development in central cities is to foster the right kind of enforcement, rather than having weak enforcement of building regulations."

Spence (2007) examined the linkage between building code enforcement and outcomes in natural disasters. He found that, "The widespread destruction of buildings in the earthquakes of Kocaeli, Turkey, in 1999 and Gujarat, India, in 2001 was not due to inadequate codes. Destruction occurred because codes were not generally adopted." His finding supports the assertion that adoption and enforcement of modern codes can prevent catastrophes in large natural disasters.

Burby (2006) drew similar conclusions for U.S. construction subject to hurricanes, citing prior authors who found that "In South Carolina, building code violations were found to be an important cause of damages from Hurricane Hugo in 1989. In South Florida, a quarter of the $16 billion in insured losses from Hurricane Andrew in 1992 were attributed to Dade County's failure to enforce its building code."

NEHRP Consultants Joint Venture (2013) examined the costs and benefits associated with Memphis, Tennessee, adopting the 2003 IBC in place of the 1999 *Standard Building Code*. Examining six particular buildings, they found that the marginal cost to adopt the IBC's seismic design requirements rather than those of the 1999 SBC ranged from zero to 1.0%. They found that the 2003 IBC would produce better seismic performance through higher design base shear and detailing requirements that improve strength or structural behavior in the inelastic range of response. They also concluded that, "Requirements for seismic bracing and anchorage of nonstructural components reduce potential for nonstructural damage and loss of building (or system) functionality."

FEMA (2014e) estimated losses avoided as a result of adopting and enforcing I-Codes. In particular, the study estimated the average annualized losses from flooding, hurricane, and earthquake among 702,000 land parcels in eight southeastern states of FEMA Region IV, thanks to provisions of the I-Codes that differ from prior codes. Flood provisions include requirements for foundation type and additional elevation above BFE. Hurricane provisions include opening protection (shutters), continuous load path, roof-deck attachment, roof cover, and strength and reinforcing in masonry wall systems. Seismic provisions require the design of new buildings considering the site-specific seismic hazard. The authors estimated a total of approximately $500 million average annualized loss avoided at these 702,000 parcels, mostly from hurricane and flood losses avoided in Florida.

Approximately one-third of U.S. communities have not adopted or do not fully enforce the I-Codes. Doing so comes with up-front costs of potentially higher construction costs and enforcements costs to the local jurisdiction, but provides benefits of greater life safety and property protection in natural disasters, and, perhaps, lower long-term operating and maintenance costs. Code adoption and enforcement could provide buyers with a lower total cost of ownership in many places, and a community BCR in excess of 1.0. If true, the long-term owner who opts to build above code in a community where no code is adopted or enforced would enjoy a BCR greater than those estimated here for an owner whose baseline is the 2015 I-Codes. However, the total cost of ownership to a developer with a short-term ownership horizon might be higher. The developer would bear the initial burden of a higher construction cost, but would own the property too briefly to enjoy savings from lower maintenance costs and lower repair costs after future natural disasters.

The adoption and enforcement of modern codes seems worth special study, but for reasons already stated in section 3.3.3, the 2017 Interim Study focuses on exceeding I-Codes where they are already in force. Later examination within the ongoing study may identify benefits and costs of adopting and enforcing I-Codes where they are not currently in force, or where important resilience features are weakened.

3.4 Estimating Benefits and Costs of Exceeding Code Requirements

Simmons et al. (2015) recently estimated a BCR of approximately 3.2 for the City of Moore, Oklahoma's enhancements to wind design requirements. They estimated benefits in terms of reduced future insurance losses, which would include many, though not all, of the benefit categories in Box 1-3.

Awando et al. (n.d.) studied the IBHS's FORTIFIED Home program. That brief study, based on 321 data points purchased from CoreLogic, estimated the marginal effect of FORTIFIED home construction standards on home resale value while controlling for other housing characteristics. The authors found that switching from a conventional construction standard to a FORTIFIED designation increased the resale value of the home by 6.8%.

3.5 Efforts to Estimate Benefits and Costs of Federal Grants

FEMA requires BCA of most proposed natural hazard mitigation it is asked to fund. To aid those analyses, FEMA developed BCA tools. On January 10, 2017, FEMA released the BCA Tool version 5.3.0 to demonstrate cost-effectiveness for FEMA's Hazard Mitigation Assistance (HMA) grant programs. Some major features include: updated standard economic values utilized in analysis; an aquifer storage and recovery module for drought mitigation; incorporation of climate resilient mitigation activities, expansion of ecosystem service benefits; updated tornado recurrence information in the saferoom module; and updated hurricane wind and earthquake hazard data sets.[8]

The 2005 *Mitigation Saves* study estimated the BCR of FEMA-funded natural hazard mitigation between 1993 and 2003. Rose et al. (2007) offered a synopsis of the study: The 2005 study performed an independent assessment of the benefits and costs of mitigating hurricane, flood,

[8] See https://www.fema.gov/benefit-cost-analysis for more information.

and earthquake risk, mostly in existing public buildings. That study used sampling to estimate the benefits and costs of a few dozen grants, extrapolated to the population of grants, and found that the $3.5 billion in mitigation spending will save society about $14 billion in avoided future building repair costs, content losses, direct and indirect BI, deaths and nonfatal injuries, and environmental and historical value.

The National Center for Environmental Economics (2010) offered general guidance on BCA. Particularly relevant is its guidance on selecting discount rates. Furthermore, the OMB (Government Publishing Office 2016) provided guidelines on discount rate values based on treasury notes and bonds with various maturities. The discount rate is the price or value of money that reflects the rate at which society is willing to postpone a marginal unit of current consumption in exchange for more future consumption and the marginal social rate of return on private investment (also termed marginal social opportunity cost of capital). An important aspect of the guidance is that federal agencies are instructed to apply 3% and 7% annual discount rates to future costs and benefits, including not just the time value of money, but also the time value of human life. That is, one must apply 3% and 7% discount rates to savings associated with avoided future deaths and nonfatal injuries. Using high discount rates reduces the apparent cost-effectiveness of natural hazard mitigation compared with lower discount rates.

Since the *2017 Interim Report* is an independent assessment of the costs and benefits of natural hazard mitigation, it is important to consider other standard texts on BCA. Among the most highly cited texts on engineering economic analysis, Newnan (1983) recommended that engineers use the after-inflation cost of borrowing if an investment will be paid for with borrowed funds, as in most cases of new design and costly retrofit.

Zuang et al. (2007) offered a survey of discount rates for BCA, and showed that some agencies use discount rates less than 1% and others as high as 10%. Some are based on the cost of borrowing. Others considered the social rate of time preference (SRTP), that is, “the rate at which society is willing to postpone a marginal unit of current consumption in exchange for more future consumption.” Still others use the marginal social rate of return on private investment, also termed the marginal social opportunity cost of capital. See Appendix H for more discussion on discount rates, and how they are handled in this Interim Study.

3.6 Methods to Quantify Business Interruption Losses

Disasters can cause costly BI losses. The inherent interdependencies across various sectors of the economy further exacerbate the direct effects of disruptive events, often resulting in significant ripple effects. A survey by Webb et al. (2000) indicates that the direct and indirect BI losses triggered by disasters can be as significant as the magnitude of the resulting physical infrastructure and property damages, and represent key contributors to disaster risk. McMahon and Friedman (2016) pointed to just-in-time inventory management systems as aggravating supply-chain losses. Notably, Allianz Global Corporate & Specialty (2015) asserted that BI losses to date account for a much higher percentage of the total loss than it did a decade ago. A more recent study by Varney (2016) further emphasized that BI losses have been ranked in the top spot of business risks four years in a row. In estimating BI losses, one must understand the magnitude and extent of linkages that exist across interdependent sectors of the affected regional economy.

Wassily Leontief was awarded a Nobel Prize in Economics in 1973 for what became known as the input-output (IO) model for the economy (Leontief, 1936). Miller and Blair (2009) provide a comprehensive introduction of the model and its applications. Leontief's IO model describes the equilibrium behavior of both regional and national economies (Isard, 1960). The IO model is a useful tool in economic decision-making processes used in many countries—it presents a framework that is capable of describing the interactive nature of transactions among economic systems. Extensions and current frontiers on IO analysis can be found in Dietzenbacher and Lahr (2004). It is worth noting that the traditional use of IO analysis for estimating the effects of economic shifts (e.g., changes in consumption) has been extended to other applications such as disaster risk management, environmental impact analysis, and energy consumption, among many others. For example, IO analysis was used to estimate the economic impacts of the earthquake-induced disruption of lifelines in the conterminous United States (Applied Technology Council et al., 1991) and can be linked with the direct building occupancy losses that can be extracted from Hazus. (FEMA developed the Hazus software to estimate potential losses in disasters.[9])

The IO model and an extension known as computable general equilibrium (CGE) analysis are two of the most popular methods typically used in evaluating the efficacy of resilience management to reduce BI and other economic losses in interdependent sectors. Rose (2009) provided detailed reviews of economic resilience definitions, categories, and enhancement strategies. Furthermore, innovations in disaster resilience policy and practical applications to workforce, infrastructure, and economic sectors have been developed by the Resilient Organizations (2017). To complement rebuilding efforts in the aftermath of disasters, Finn et al. (2016) explore the concept of citizen-based planning and long-term resilience thinking as applied to communities hit by Hurricane Sandy. CGE analysis offers a more complex modeling framework for assessing the impacts of economic and disaster resilience policies (Rose and Liao 2005). It shares the capabilities of IO models in itemizing the effects of a disruptive event across interdependent sectors. In addition, CGE's explicit inclusion of prices and input substitution via elasticity parameters has the potential to more accurately describe the efficacy of strategies for allocating constrained resources, with the aim of minimizing BI and other economic losses. Nonetheless, the estimation of BI losses using IO modeling and data analysis are more practical, because CGE models are complex, expensive, and not readily available for small geographic areas. The U.S. Bureau of Economic Analysis (BEA) is the agency primarily responsible for releasing the official IO accounts for the United States at both national and regional levels.

Note that, in some cases, Hazus software cannot be used to estimate BI losses, e.g., for designing to exceed I-Code requirements for seismic design of new buildings. Chapter 4 presents a customized IO model to deal with such cases.

[9] See www.fema.gov/hazus for more information.

3.7 Methods to Quantify Social Impacts

Despite the decade or so since the 2005 *Mitigation Saves* study, little, if any, advancement in methodologies for quantifying societal benefits of hazard mitigation has occurred. In a 2014 review of studies focused on BCA, Shreve and Kelman (2014) reviewed 28 studies that assessed the benefits and costs of mitigation, highlighting both what was included in the analysis and the limitations of the study. Based on the data presented, few studies included societal benefits when analyzing the BCR. In the few studies in which it was included, avoided losses of life were primarily included as the major societal benefit. The article noted a few exceptions that broaden the analysis to include health impacts and displacement. When specified, the authors of these studies almost always acknowledged omitting social benefits; most often because they were beyond the scope of the project.

The 2017 Interim Study aims, among other things, to include some broader social benefits beyond those included in the 2005 *Mitigation Saves* study. One of the major limitations of including these types of costs is that they often require significant primary research that is beyond the scope of the project. However, some recent work by Sutley et al. (2016) led to the development of a methodology to include PTSD costs. This work analyzed data to determine a cost-benefit for earthquake structural mitigation in the City of Los Angeles, integrating a methodology for inclusion of PTSD costs. The method used in the 2017 Interim Study is modeled on the work by Sutley et al. (2016a, 2016b).

In the *Interim Report*, the project team used a review of the literature to set the rate of PTSD at each damage state to be the equivalent of a severe injury, that is, Hazus' injury level 3. While the Hazus injury scale is problematic to map to abbreviated injury scale (AIS) categories, for consistency, the project team used the same mapping as the 2005 *Mitigation Saves* study.

The rate of PTSD is probably affected by age, ethnicity, family structure, gender, income, and other factors that may be impractical to address in this Interim Study. See, for example, Jennings (2015) and Sutley et al. (2016).

The project team determined the costs of PTSD based on the calculated PTSD rate and estimated costs for treatment, absenteeism, and cut back days. The team estimated the cost of treatment at $5,400 per year based on a study on Veterans conducted by the Congressional Budget Office (CBO, 2012). Jennings (2015) calculated costs of absenteeism and cut back days as a function of the annual number of work days lost (Kessler and Frank, 1997) and mean salary of the population.

It is important to note that Sutley focused only on earthquakes in the City of Los Angeles, and it used socioeconomic data from the U.S. Census Bureau. However, a review of rates of PTSD after hurricanes (Perilla et al., 2002; Galea et al., 2008) and floods (McMillen et al., 2002; Norris et al., 2004) supported using the same rates across hazards. The project team modified this method for inclusion in the 2017 study, as discussed later in this *Interim Report*.

3.8 Methods to Quantify Other Intangibles

The project team addressed other intangibles, such as environmental damage and loss of cultural value through damage to historical buildings, with benefit-estimate-transfer approaches. These vary by the type of benefit to be recognized: recreational water quality; drinking water; outdoor recreation trips; hazardous waste; wetlands; aesthetics; health and safety benefits from underground power lines; and cultural and historical resources. (See Appendix J of the 2005 *Mitigation Saves* study for details.)

3.9 Land Use Planning to Reduce Flood Hazard

Flood risk can be reduced through land-use planning. Land use types, such as green spaces and wetlands, collect water and mitigate flooding. Conversely, development that is heavy on asphalt and concrete creates impervious surfaces, increasing runoff, flood velocity, and damage potential. Infrastructure development can affect the height of flooding upstream or downstream. The NFIP does not allow development in floodways that would raise the BFE upstream or downstream by more than 1 foot (ICC, 2014). Floodways are the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the water surface elevation more than a designated height. Because of the way the NFIP maps floodways, the NFIP allows new development in the SFHA (the 1% annual chance floodplain) to increase flooding by 1 foot. Likewise, the I-Codes do not allow development to increase the BFE at all (ICC, 2014).

The Association of State Floodplain Managers (ASFPM) advocates a policy of no adverse impact—development should not increase flood risk, increase costs, or lower water quality for other people or structures in the watershed (2016, 2003). ASFPM has many examples of flood mitigation management that can help a community satisfy the no-adverse-impact policy. These measures include removing or relocating structures from floodplains; preventing development in floodplains; zoning areas of land for particular uses such as agriculture and green space; preserving wetlands; improving water drainage and storage; using green infrastructure (e.g., parks and urban greenways) and materials; and reducing the coverage of impervious surfaces.

Integrated water resources management and its offshoot integrated flood mitigation (IFM) provide a framework for reducing flood damages while promoting economic, social, and ecological benefits. This is gaining favor over a gray-infrastructure strategy of relying on dams and levees to attempt to contain rivers and prevent flooding altogether (e.g., Santoto et al., 2013). While these structural measures may still be used, other measures are also available to distribute and absorb water flow while limiting the amount of infrastructure in the path of flood waters. IFM plans recognize that a river is a complex system, and all parts of it require consideration. Interactions between water, vegetation, and soils contribute to changes in stream velocity that can have impacts at points upstream or downstream.

Owners of properties that have sustained significant flood damage have the option to allow the government to acquire the property, also known as a buyout. FEMA works with state governments to finance this action. The owner receives the fair market value for the property. The property is demolished, permanently avoiding future damages and allowing the floodplain to absorb more water without damaging other structures.

Land use decisions are generally made at the state and local level. However, though land use planning and floodplain management are conducted by municipalities and states, floods are not restricted by political boundaries.

The NFIP's CRS provides incentives for a wide variety of mitigation measures. Communities can earn a reduction in flood insurance premiums by implementing these measures. Over 1,000 communities participate in the CRS. This is less than 10% of the communities in NFIP, but nearly 70% of NFIP policies are in CRS communities. Florida and other parts of the southeastern United States have the highest participation in the CRS.

While the costs of property acquisition and demolition or relocation are high, future losses are completely avoided. Acquired land may be used for public spaces such as parks, creating additional co-benefits. FEMA has participated in the acquisition of several thousand properties over the past decade (FEMA, 2017b, ASFPM, 2016). However, there are over 5 million properties that have NFIP policies (FEMA, 2016a), so relocation and acquisition account for a small percentage of mitigation actions taken.

Nature-based solutions or green infrastructure offer some ability to adapt to changing flood risks. It also offers many benefits and opportunities for recreation, ecological services, and economic development (Kousky and Walls, 2014; ASFPM, 2003) over gray infrastructure, such as the use of tunnels and wastewater treatment plants to collect and discharge storm water. Gray infrastructure has both high initial costs of development and maintenance costs. It is inflexible and could exacerbate flooding if its limits are exceeded. Green infrastructure is becoming more common in either replacing or complementing gray infrastructure, particularly in urban areas.

IFM strategies may require systemic changes to floodplain management and cause long-lasting socioeconomic changes in sectors such as housing, utilities, and transportation (Kundzewicz et al., 2010). Redesigning land use code practices for a community may be met with resistance, making communication even more important (ASFPM, 2016).

In one study, FEMA (2013b) identified 10 success stories of integrating hazard mitigation into local planning. The examples were evenly distributed throughout the United States and included entire states and individual cities and counties. The actions taken in these case studies included improving and coordinating local plans, improving storm water drainage, adding sustainable infrastructure, and starting outreach programs. While the benefits of integrating land use planning can be substantial, each community has different characteristics and needs and chooses to take different complex actions. Generalizing and quantifying the benefits of land use planning may not be possible.

The 2005 *Mitigation Saves* study addressed the cost-effectiveness of federal buyouts. The federal mitigation grants the 2017 project team studied also focused on buyouts in order to establish comparable figures with the 2005 study and because, while considered a costly mitigation option, buyouts do provide the greatest societal benefit in the form of permanent avoidance of loss.

3.10 Flood Risk Modeling

Flood risk modeling refers to the process of estimating potential losses and damage for a particular asset at risk to a particular flooding event. Assets can include buildings, bridges, utility lines, farms, humans, animal stock, and others. A flood risk model can therefore be thought of as a product of the probability of hazards occurrence, nature of exposure, and the degree of vulnerability of the elements at risk (Rashed and Weeks, 2003). A community can be exposed to flood hazards but, if it has taken measures to lower its vulnerability, then it will not experience higher losses. Likewise, a highly vulnerable community will not experience any loss if does not actually experience flooding (Rashed, 2005).

A typical flood risk modeling procedure comprises the following tasks:

1. Generating a flood hazard scenario, and mapping the extent and intensity of flooding in a region based on hydro meteorological data and information about the terrain within the floodplain. The scenario can represent a historical occurrence of a flood in a region, or a statistical estimate of the probability of occurrence of a flooding event with a particular intensity in that region.
2. Creating an inventory of the nature and location of all "elements at risk" and assessing their vulnerability to flooding according to predefined assumptions about demographics, buildings, structures, and other vulnerable elements. The predefined assumptions are typically based on historical records that report the degree of damage that elements of the same kind have experienced in the past as a result of flooding. For example, the vulnerability of a particular building type can be represented by an empirical damage curve created from recording different degrees of damage this type of building has experienced from different flooding events in the past.
3. Assessing the nature and degree of loss an element of risk may experience as a function of the flooding intensity, its vulnerability, and its exposure. The exposure is typically determined by its location within the floodplain and its level of inundation.

In mitigation studies, proper modeling of flood risks is crucial to the proper assessment of mitigation strategies. One common way to assess mitigation strategies is through the BCA of mitigation actions, where the benefit of an action is estimated in the form of the loss avoided from implementing that action. Avoided flood losses are typically estimated by running two scenarios of a flood risk model, one before the mitigation action is implemented, and one after its implementation. The difference in the losses generated from each scenario reflect the benefit gained from the implementation of the mitigation action.

BCA has been the principal decision-making technique for water resources planning since the enactment of the Flood Control Act of 1936. The primary reason for this is the fundamental framework of rational analysis that underpins the comparison of social benefits with social costs of various projects. Though BCA data are derived primarily from economic markets, innovations by analysts have enabled economic values to be derived for environmental and social amenities and services that were often overlooked in previous studies. For example, improvements in multiple-objective water resources planning and management pioneered in the late 1950s and early 1960s by the Harvard Water Program preceded the maturation of environmental economics as an academic discipline (see Eckstein 1958; Maass et al. 1962). Integration of new knowledge in the USACE *Principles and Guidelines*, which sets the criteria for BCA studies, has been fairly continuous (2013). In 2009, the Corps issued its guidance document for a national flood risk management program, and has fostered advances in integrated water resources management with environmental operating principles (USACE 2012).

As a decision guide for human investment, BCA reveals the most economically efficient choices that provide the highest net social benefits to decision-makers. For planners tasked with the challenge of mitigating episodic flood hazards, BCA provides analysts with a detailed understanding of what specific elements of a mitigation plan or process improve the overall economic viability of any locality (e.g. Birchard et al., 2016). While many analysts have pointed out the shortcomings of BCA with respect to key intangibles such as the value of human life, the technique has provided decision-makers with a robust data-driven approach that is both reproducible and transparent. Similar to the lag time incurred in the modernization of building codes, there has been a comparable lag in efforts to keep BCA current with new knowledge and improved methods of decision-making. The findings of this Interim Study illustrate well the ability of BCA to incorporate a variety of factors deemed important to decision-makers, and enable them to make informed choices that are both socially desirable and economically appealing.

The 2005 *Mitigation Saves* study used BCA of FEMA mitigation grants and eight community studies. The flood module of FEMA's Hazus software had not yet been fully developed, so other methods were necessary. The 2005 project team calculated BCRs of flood mitigation by identifying the locations of buildings affected, calculating the potential for hazards in that location, calculating the vulnerability (potential for damage) before and after mitigation, estimating the present value of losses under both conditions, and dividing the difference by the cost of mitigation.

The *2017 Interim Report* uses Hazus software to conduct BCA of both above-code design and public-sector mitigation for riverine floods. The 2017 project team used the flood module of FEMA's Hazus release 3.2 software for this Interim Study. (Details of the Hazus loss estimation methodology for the flood hazard are described in the Hazus 2.1 Flood Technical Manual (FEMA 2006c) while key aspects of the model relevant to this project are described in this Interim Study.)

Hazus model components include the flood hazard; inventory; and damage and loss models. Hazus allows users to apply default settings and databases for each of the inputs, but it also provides options for incorporating detailed data, if available, to reduce the margin of error and thereby expand the potential applicability of the model for a broader range of uses.

The building inventory models the location, characteristics, and property value of buildings in the Interim Study area. Except for selected building types such as schools and fire stations, the default Hazus building inventory, referred to as the GBS, aggregates to 2010 census blocks in the Hazus 3.2 flood model. The GBS inventory is compiled using a variety of data resources such as the 2010 census (to determine building count and distribution) and RSMeans (to estimate building replacement costs). Hazus categorizes the GBS into seven broad occupancy classes (e.g. residential, commercial, etc.) and 33 subclasses referred to as specific occupancies (e.g. single family, manufactured housing, etc.). Hazus has traditionally assumed that buildings in the GBS are evenly distributed throughout a census block, but recent releases now apply asymmetrically adjusted census block boundaries to better ensure that buildings are more likely to be placed in populated areas. That methodology uses 2011 satellite data to clip the census blocks to remove typically unpopulated areas such as forests, vacant land and water bodies. For blocks that are intersected by the calculated flood hazard extent this should more accurately estimate the number of buildings damaged in those blocks. In general, this reduces estimated losses, particularly in rural areas.

The square footage of buildings in the default Hazus inventory is estimated using data on the heated floor area from the Energy Information Administration (EIA). The area is converted into income groups that vary by geographic region. Regional breakdowns of the percentage of buildings that have different occupancy types, number of stories, foundation types, age, and other characteristics are downscaled to estimate the number of buildings with those properties in each block.

The Hazus Comprehensive Database Management System allows users to supplement or entirely replace default inventory with information on specific buildings or to create more accurate aggregated data. One particularly useful component of the Hazus inventory is referred to as user-defined facilities (UDF). Hazus requires UDF to have information on the foundation type, number of stories, first floor elevation, and occupancy class of individual buildings.

Hazus uses depth-damage functions to associate the depth of water with the amount of damage a building sustains. The functions require information on building characteristics as well as the depth of flood waters. The main source of depth-damage functions is the USACE. There are different groups of functions for different geographic regions. Each grid cell in the floodplain is assigned the appropriate flood depth and resulting damage value for the depth damage function. The number of cells for each flood depth in a census block is used to weight damage at that depth for each occupancy type. This approach means that results for individual census blocks may not be accurate, but high and low estimates tend to balance out if a larger area, such as a county, is considered. Users can edit the default functions or import functions from other sources. Hazus applies the same depth-damage functions to UDF as it does for the GBS. This results in estimates for building loss amount, building damage percent, content loss amount, and inventory loss amount.

Hazus estimates losses in terms of both the cost of rebuilding and replacing buildings and other structures, as well as losses from disruption to the community, such as businesses being unable to operate. However, not all ripple effects of a disaster on the socioeconomic landscape can be represented. Estimates of direct physical damage to the GBS require building occupancy class, foundation type, first floor elevation, and flood depth. Hazus uses the depth damage functions to calculate a damage state for a census block as a percentage of the total building value damaged. The building states are separated into different percentage categories to aggregate estimates. Estimated building replacement costs are based on the building's size and occupancy class. The contents replacement value of a structure is assumed to be a percentage of the structure's replacement value, depending on the occupancy type. Business inventory values are calculated using the building's annual sales per square foot. The contents replacement value and building inventory value are multiplied by the appropriate depth-damage function to estimate losses.

Restoration time factors into many indirect loss calculations. Tables based on occupancy, flood depth, and location relative to the SFHA determine the restoration time in months. This includes the time to repair the building, remove debris, approve permits, and inspect buildings. If building damage is at least 50%, it is assumed that the building will be demolished and rebuilt (with modifications if the building is in the SFHA). Relocation costs are disruption costs that building owners experience due to moving and renting temporary space, depending on the occupancy type. They are incurred when building damage is greater than 10%. Business proprietor losses, wage losses, and output (sales) losses are calculated using the amount of time to restore function, tables for building occupancy, the square footage of buildings, and income recapture. The number of days of employment lost is calculated by multiplying output loss by each industry's employment/output ratio. Rental income losses are calculated using the occupancy, square footage, damage state, rental cost, and recovery time.

Expected annualized loss (EAL), sometime called average annualized loss (AAL), can be calculated by running Hazus for multiple flood probabilities and summing the product of the probabilities and damages caused. EAL can be compared for scenarios with and without mitigation strategies such as building elevation or removal to evaluate the losses those strategies would avoid (Kousky and Walls 2014). In the FEMA Region IV losses avoided study discussed in section 3.2.2, it was estimated that losses avoided were underestimated by 10 to 20% because of missing data and data refinement. The assumption of perfect building code enforcement led to a 5 to 10% overestimate of losses avoided. It is possible to standardize estimates of enforcement based on CRS and BCEGS data. That study used lower-, average-, and upper-bound depth damage functions to obtain a range of loss estimates.

Hazus makes many assumptions in all aspects of its analysis, and these can contribute to a high degree of model uncertainty and sensitivity (Tate et al., 2015, Kousky and Walls, 2014, FEMA, 2006c). Hazus may be best utilized to estimate the magnitude of damage rather than make precise predictions (Kousky and Walls 2014). It does not output a measure of uncertainty for its flood hazard-related estimates. Hazus gives users the option to use default settings or provide more-detailed information for several analysis inputs. In general, one would expect that more-detailed user-defined data would produce more-accurate estimates. However, Tate et al. (2015) found that using a combination of default and more-detailed datasets can produce unstable results. Ideally, more detailed inputs would always be used, but this is not always possible or practical due to resource availability and computation time.

3.11 Estimating Future Growth

Some costs and benefits change over time as the population grows or moves. The 2017 Interim Study attempts to estimate costs and benefits decades into the future. As a baseline or minimum, one can project growth in new buildings by recognizing that new buildings are added on average at a rate of approximately 0.01 per year times the existing building stock (e.g., Ravetz, 2008). If a certain census tract has 100 buildings at the end of 2016, one can estimate that it will have on average 101 at the end of 2017, 102.01 at the end of 2018, and so on ($101 \cdot 1.01 = 102.01$), or in general 1.01^n times the original estimate at the end of n years. This simplistic approach does not account for population spread, e.g., people moving into previously unoccupied places, or growth in one place differing from the pattern of growth in another, but it is easy.

A more complex approach: the U.S. Census Bureau offers state population projections through 2030 based on Census 2000 (UCSB 2004). This approach offers the advantage of authoritativeness (U.S. Census Bureau) and carries some disadvantages: (1) complexity: 50 state-level extrapolations rather than one simple mathematical rule; (2) somewhat detached from the value of exposed buildings: change in population is not the same as construction of new buildings; (3) insufficient duration: the analysis requires extrapolating growth of the building stock for much more than 15 years.

3.12 Alternatives to BCA for Natural Hazard Mitigation

For a widely used textbook on engineering economics, see Park et al. (2007). Park and other common textbooks identify BCA as one of several approaches to quantify the desirability of an investment. One can also estimate return on investment (ROI), in which one calculates the ratio of net benefits (the difference between benefits and cost) to total cost. It measures profitability. A higher ROI means a more profitable investment. It uses the same quantities as BCR. Or one can measure the desirability of an investment with an internal rate of return (IRR): the discount rate at which the present value of all future cash flow is equal to the initial investment or, in other words, the rate at which an investment breaks even. One can measure the desirability of an investment with its expected value of utility, a somewhat abstract measure of satisfaction, preference, or happiness, usually of an individual, that underpins game theory and Stanford-style decision analysis.

4 Methodology Employed in This Study

4.1 Engineering Approach to BCA

As done in the 2005 *Mitigation Saves* study, the project team for the *2017 Interim Report* used an engineering approach to estimate BCR. Figure 4-1 and the process below summarize the steps of an "engineering approach."

1. ***Exposure data***. Acquire available data about the assets exposed to loss. Often these data come in formats intended for uses other than those to which the analyst intends to put them.

2. ***Asset analysis.*** Interpret the exposure data to estimate the engineering attributes of the assets exposed to loss. These attributes (denoted by A) may include quantity (e.g., square footage), value (e.g., replacement cost), and other engineering characteristics (e.g., model building type) exposed to loss in one or more small geographic areas. Occasionally assets are described probabilistically (e.g., the probability P that each asset has some set of attributes A, given the exposure data D, denoted by $P[A|D]$). Combine the data D and the asset model $P[A|D]$ to estimate the probability that the assets actually have attributes A, denoted by $P[A]$.

3. ***Hazard analysis.*** Select one or more measures of environmental excitation H to which the assets are assumed sensitive (e.g., peak wind gust velocity at 33 ft elevation in exposure category C), and estimate the relationship between the severity of those measures and the frequency (events per unit time) with which each of many levels of excitation is exceeded. The relationship is denoted as $P[H|A]$, (e.g., the probability that the environmental excitation will take on value H, given attributes A). Combines $P[A]$ and $P[H|A]$ to estimate the probability of various levels of excitation, denoted by $P[H]$.

4. ***Loss analysis.*** Select loss measures to quantify, for example, property repair costs, casualties, duration of loss of function, etc. For each taxonomic group in the asset analysis, estimate the relationship between the measure of environmental excitation H and each loss measure L. This relationship is called the vulnerability model, denoted by $P[L|H]$. Loss measures are usually expressed at least in terms of expected value, and often in terms of the probability distribution of loss conditioned on (e.g., given a particular level of) environmental excitation. Use the theorem of total probability to estimate either the expected value of loss or the probability of exceeding one or more levels of loss, for each loss measure. Sometimes one estimates and separately reports various contributors to loss by asset class, by geographic area, by loss category, etc. One combines $P[H]$ and $P[L|H]$ to estimate the probability of various level of loss, denoted by $P[L]$.

5. ***Decision-making.*** The results of the loss analysis are almost always used to inform some risk-management decision. Such decisions always involve choosing between two or more alternative actions, and often require the analyst to repeat the analysis under the different conditions of each alternative, such as as-is and assuming some strengthening occurs.

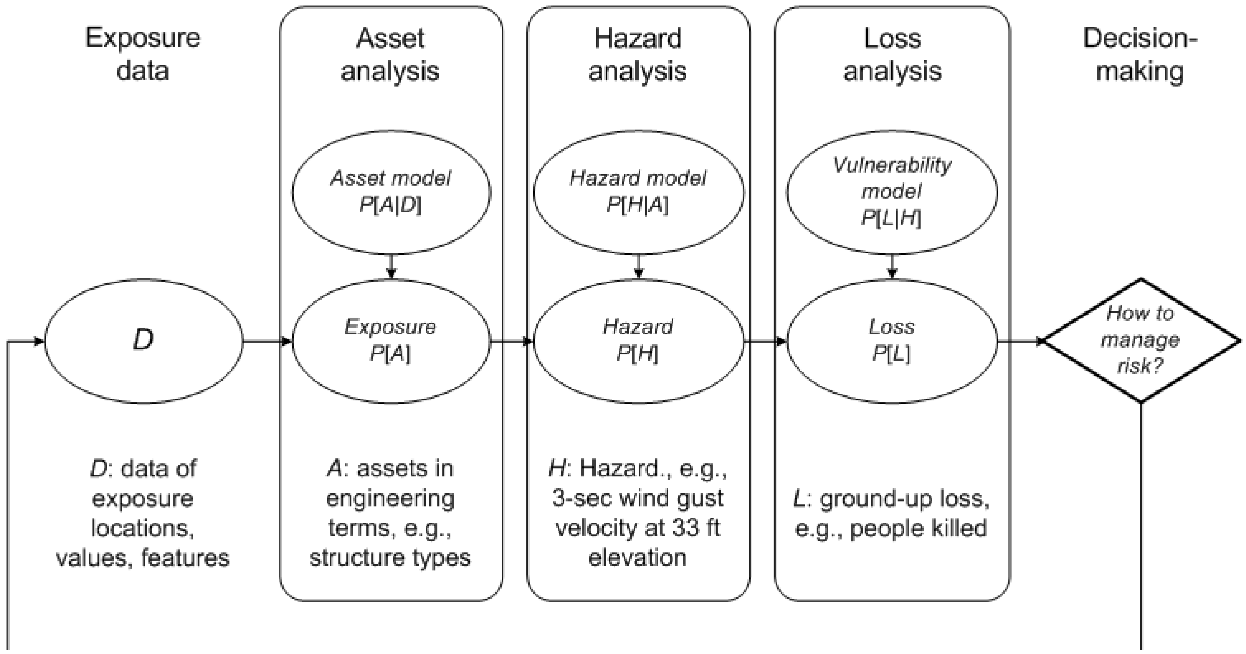

Figure 4-1. An engineering approach to risk analysis (image credit: Porter 2017, used with permission).

4.2 BCA for Mitigation Estimates Long-Term Averages

This project quantifies the desirability of natural hazard mitigation using BCRs, meaning the ratio of the present value of reduced future losses (the benefit) to the added construction cost or retrofit cost of those mitigation efforts (the cost). The benefits average over time, considering large and small disasters that may occur at any point in time during the economic life of the mitigation measure, and considering the likelihood that these events will happen at all.

The more likely a disaster is to occur, or the more severe its outcomes, the greater the expected value of the benefit that mitigation will produce. In the case of a mitigation measure that applies to many buildings, the more buildings that are likely to be affected by a disaster during their economic life, the greater the calculated benefit, because the benefit represents an average over all the mitigated buildings.

As a consequence of this averaging process, BCA has an important limitation when applied to natural hazard mitigation: a BCR by itself tells the decision-maker nothing about the chance that the mitigation measure will actually be needed during the economic life of a building. The rarer the disaster, the less likely that a mitigation measure will actually produce value by reducing loss. While the BCR accounts for that likelihood through the averaging process, some decision-makers may object to the fact that money is definitely being spent up front to reduce a loss that may never occur to their building, and that the benefit of mitigation may only be enjoyed by somebody else, or by nobody at all.

4.3 Calculating Aggregate Benefit-Cost Ratio

This project aims ultimately to estimate the aggregate nationwide BCR for a suite of natural hazard mitigation measures, along with BCRs for subsets of mitigation efforts, such as by peril. Once a sufficient number of mitigation strategies and their BCRs are studied the project team will calculate the aggregate BCR for public- and private-sector investment in mitigation by aggregating results from each strategy.[10] In the case of the 2005*Mitigation Saves* study, the overall BCR of 4.0 was calculated based on a sample of particular mitigation measures. The sample was scaled up to estimate the benefit of all FEMA-funded mitigation from 1993 to 2003. The same scaling-up procedure is used here. Equations 4-1 through 4-7 show how that scaling works. The equations can be explained as a four-step process:

Step 1. Select a sample mitigation effort. Calculate its expected (e.g., average) annualized loss (EAL) due to natural disasters in the absence of mitigation strategy i, as shown in Equation 4-1. In the equation, $\lambda(x)$ denotes the mean exceedance rate of environmental excitation x (for example, wind speed) to a sample facility; $y(x)$ denotes the mean loss to the sample facility (as a fraction of replacement value) when subjected to excitation x absent mitigation strategy i; and V denotes the value exposed to loss, absent the mitigation strategy. Note that the vulnerability function $y(x)$ represents more than property loss. It also comprises time-element losses, losses associated with deaths and nonfatal injuries, loss of employment, and may include a variety of financial, social, and cultural losses. Then repeat this calculation for the same facility but under remediated conditions, that is, with a mitigation strategy applied. That is, calculate *EAL'* (what-if-mitigated *EAL*) using a what-if-mitigated vulnerability function $y'(x)$, using the same Equation 4-1.

Note that some mitigation measures can produce benefits for several different perils, such as engineered tie-down systems. Equation 4-1 would be applied separately for each peril and then summed to estimate *EAL* and *EAL'* from each relevant peril. Note also that some perils change over time: for example, a recent model of California seismic hazard accounts for estimated time dependency (Field et al. 2015). Sea level rise changes the coastal flooding hazard and tsunami hazard.

In some situations, Equation 4-1 involves integration over time. That is, V, G, and perhaps y may also be functions of time, so the equation more properly has a second integral over time. The second integral is omitted from the equation for clarity, but this work attempts wherever practical to quantify the three variables as functions of time and carry out the second integral. For example, where dealing with the costs and benefits of designing new buildings to exceed I-Code minima, the project team recognized that the quantity of buildings (an aspect of V) grows approximately exponentially. Coastal flooding hazard (G) will change with local sea level rise (LSL), which may vary nonlinearly with time. This aspect may generate controversy and criticism, so the project team attempted to use the best practical science and engineering to model how exposure and hazard will change over time in the future. The Interim Study documents reasonable alternatives and explains choices later in the work. (Nonstationary vulnerability is more dubious than time-varying exposure and hazard. The temporal changes of material strength and stiffness observed in the laboratory, such as with

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[10] Given the limited number of mitigation strategies covered in this Interim Study, the project team decided not to provide an aggregate BCR at this time to avoid future confusion.

concrete cylinder strength, are small compared with uncertainty in vulnerability. The analysis generally assumes therefore that engineering vulnerability *y* remains constant over time.)

Step 2. Calculate the benefits for an individual mitigation strategy (denoted by b_i) over time *t*, as shown in Equation 4-2. In that equation, *EAL* and *EAL'* represent the expected annualized disaster losses to a sample facility before and after applying mitigation strategy *i*. The term *r* denotes the after-inflation annual discount rate (which measures the time value of money), and *t* denotes the number of years that mitigation strategy *i* is effective. Multiply b_i by the ratio of nationwide expenditures to the expenditures represented by the sample (E_i and e_i respectively), as shown in Equation 4-3. The product is the nationwide benefit of strategy *i* (denoted by B_i). Note that Equation 4-2 accounts for the possibility that the mitigation measure is never actually used—that the peril does not occur during the effective life of the mitigation measure. It says that benefits do not accrue after time *t*.

Step 3. Sum over all mitigation strategies (*i* = 1 to *n*) for a first-order estimate of the nationwide aggregate benefit of all the strategies considered, as shown in Equation 4-4. Add the *synergy benefit*, that is, the benefit that accrues because of interaction between two or more mitigation strategies: strategies *i* and *j* in the double summation in Equation 4-4, or strategies *i*, *j*, and *k* in a triple summation. For example, a facility that was built stronger, with ongoing nonstructural mitigation, and uses an up-to-date business continuity plan, is likely to resume business more quickly than one where only one or two of those measures have been implemented. The term *m* in Equation 4-4 represents a multiple reflecting the fractional increase in benefit that accrues because of synergies between mitigation measures.

Step 4. Calculate the aggregate and per-strategy BCRs. The aggregate nationwide cost is calculated similarly to the first-order benefit, as in Equation 4-5. The ratio of the aggregate nationwide benefit to the aggregate nationwide cost is the aggregate nationwide BC, as in Equation 4-6. The Interim Study also includes an estimate of BCRs for individual mitigation strategies, as shown in Equation 4-7.

$$EAL = V \int_0^\infty -\frac{dG(x)}{dx} y(x) dx$$

(Equation 4-1)

$$b_i = \frac{EAL - EAL'}{r}\big(1 - exp(-rt)\big)$$

(Equation 4-2)

$$B_i = \frac{E_i}{e_i} b_i$$

(Equation 4-3)

$$B = \sum_{i=1}^{n} B_i + \sum_{i=1}^{n} \sum_{j>i}^{n} m_{i,j}\left(B_i + B_j\right) + \sum_{i=1}^{n} \sum_{j>i}^{n} \sum_{k>j}^{n} m_{i,j,k}\left(B_i + B_j + B_k\right) + \cdots$$

(Equation 4-4)

$$C = \sum_{i=1}^{n} \frac{E_i}{e_i} \cdot c_i$$

(Equation 4-5)

$$BCR = \frac{B}{C}$$

(Equation 4-6)

$$bcr_i = \frac{b_i}{c_i}$$

(Equation 4-7)

In the case of values that change over time and accumulate over a geographic area, such as codes in which effects change with population, Equation 4-1 can be recast by summing over area *A* and integrating over time *t*, as in:

$$EAL = \sum_{A} \left(V_0 \left(\int_{x=0}^{\infty} -\frac{dG(x)}{dx} y(x) dx \right) + \int_{t=0}^{T} \frac{dV}{dt} \left(\int_{x=0}^{\infty} -\frac{dG(x)}{dx} y(x) dx \right) dt \right)$$

(Equation 4-1a)

The ultimate goal is to estimate whether or not natural hazard mitigation is cost-effective, but it is only practical to calculate BCR for a sample of projects. What can one say about the true, population-wide BCR based on the sample? Sums of many uncertain numbers tend to take on a particular probability distribution—the familiar bell-shaped curve of the normal distribution. The true population-level BCR is related to the sample-average BCR through a quantity called the standard error, which is calculated using Equation 4-8. One can use that standard error to estimate the probability that mitigation is actually cost-effective (e.g., that the population-level BCR exceeds 1.0) using Equation 4-9. That is, Equation 4-9 estimates the chance that, if one were able to perform a BCA of every mitigation effort and add up all their costs and benefits, benefits would exceed costs. The equation assumes that the sample is unbiased—that, on average, if one were to select many different samples, the average of their BCRs would equal the population-level BCR. The 2005 *Mitigation Saves* study found a grant-sampling strategy that is indeed unbiased, which will be further discussed in Section 4.7.

$$s = \frac{1}{n} \cdot \sqrt{\sum_{i=1}^{n} \left(bcr_i - \overline{bcr}\right)^2}$$

(Equation 4-8)

$$P[BCR > 1] = 1 - \Phi\left(\frac{1 - \overline{bcr}}{s}\right)$$

(Equation 4-9)

In Equation 4-9, P[ ] denotes the probability that the statement inside the square brackets is true, Φ denotes the standard normal cumulative distribution function, and $\overline{bcr}$ denotes the sample average BCR, calculated as shown in Equation 4-10.

$$\overline{bcr} = \frac{1}{n}\sum_{i=1}^{n} bcr_i$$

(Equation 4-10)

4.4 Selection of Designs to Exceed 2015 I-Code Requirements

The previous section covered the calculation of BCRs for *ex post* mitigation, e.g., mitigation after a building is built (often called retrofit or remediation). This section examines *ex ante* mitigation, that is, mitigation prior to the event, in this case, constructing new buildings to exceed the current local minimum requirements. The math is largely the same.

Specifically, estimate the benefits and costs that would result from designing buildings to exceed I-Code requirements using the methods described in Section 4.1. For all perils except fire at the WUI, the project team estimated the costs and benefits of exceeding I-Code requirements relative to I-Codes published by October 2016. For simplicity, the team considered only the ordinary buildings—risk category II buildings under ASCE 7-10. The project team then estimated EAL in all the categories listed in Chapter 1. To select design options, the project team weighed the advantages and disadvantages of options discussed in Section 3.2 and selected those shown in Table 4-1 for analysis.

Peril	Selected design option	Rationale
Flood and storm surge	Increase elevation beyond the 1 foot required above BFE.	Straightforward to implement both in calculations here and in practice. All designers possess the necessary skills.
Earthquake	Increase ASCE 7-10 strength and stiffness requirements by a factor I_e.	Straightforward to implement both in calculations here and in practice. All designers possess the necessary skills. Growing support within the earthquake engineering community and a few informed building owners. Relevant to perhaps 82% of new buildings in seismic-prone areas that have adopted disaster-resistant building codes. Addresses both structural and much (though not all) nonstructural damage.
Hurricane wind	IBHS FORTIFIED Home Hurricane program.	Straightforward to implement both in calculations here and in practice. Well documented. Growing support and implementation within hurricane-prone regions.
Fire	Adopt ICC 2015 IWUIC	Strong support from the ICC. Well documented. Straightforward to implement. Readily calculated.

Table 4-1. Selected mitigation strategies for exceeding I-Code requirements.

4.5 Identifying the IEMax Level of Additional Mitigation

The selected options to exceed I-Code requirements for flood, wind, and earthquake each offer a range of design levels: one can design new buildings to be a little higher above BFE or a lot higher, for example. Under standard BCA procedures, the IEMax level of investment requires that both the total benefit exceeds the total cost and the incremental benefit exceeds the incremental cost. For example, suppose one could choose to build new buildings in coastal velocity zones (V-zones) 1 foot above BFE, 2 feet, 3 feet, 4 feet, etc.

The IEMax level of additional mitigation is the point on a geographic and mathematical basis where the last incremental improvement in the design cost-effectively captures the last incremental benefit. One of the most widely cited texts on engineering economic analysis (Newnan et al. 2006, p. 503) uses the term “best alternative” defined to be the “maximum investment such that each ratio of equivalent worth of incremental benefits to equivalent worth of incremental costs is greater than 1.0.” This Study uses IEMax to avoid the word “best,” recognizing that significant benefits can be achieved cost-effectively at various levels of design up to the IEMax, meaning that one can enjoy cost-effective improvement without designing all the way up to the IEMax level.

Suppose it is cost-effective to build 2, 3, or 4 feet above BFE on a benefit-cost basis. That is, the total benefit exceeds the total cost for each of those elevations. In each case, it costs more to build *n* + 1 feet above BFE than *n* feet, and there may be an additional benefit as well. The analyst must estimate whether the additional benefit of the additional foot—increasing from *n* feet to *n* + 1 feet—exceeds the additional cost, that is, whether the last foot of additional elevation is cost-effective.

Figure 4-2 illustrates the concept: each dot represents one possible level of design to exceed code requirements: "2" means BFE plus 2 feet, "3" means BFE plus 3 feet, etc. Each dot has a cost (its *x*-value) and a benefit (its *y*-value). ΔC denotes the incremental cost of building *n* + 1 feet rather than *n* feet above BFE, and ΔB denotes the incremental benefit. One can say that the IEMax investment is the last value of *n* + 1 for which ΔB is greater than ΔC, or in other words, ΔB/ΔC > 1.

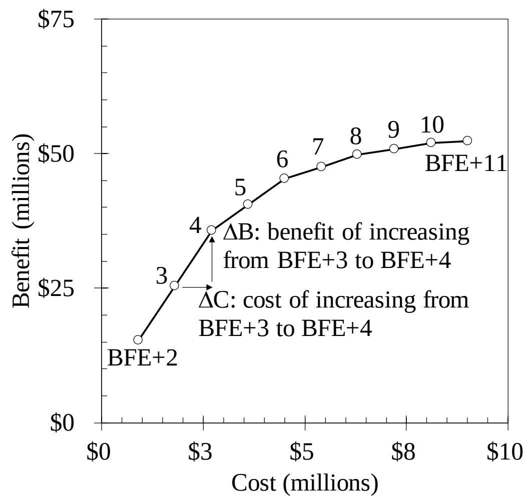

Figure 4-2. Incremental benefits and costs when evaluating a range of possible degrees of mitigation investment.

4.6 BCA of Federal Mitigation Grants

This section describes the BCA of federal mitigation grants studied in this project. The analysis involves three major steps. In Step 1, a stratified sample of mitigation grants is created. A stratified sample consists of individual grants selected according to hazard (earthquake, wind, flood, and fire) and mitigation types (project and process activities). In Step 2, the BCR for an individual project within a stratum is calculated. In Step 3, the benefits and costs from the sample are scaled up to the entire population of project and process activities, as described in the previous section.

4.7 Grant Sampling Strategy

This section only applies to the study of federally funded mitigation grants, not design to exceed I-Code requirements. Recall that Step 1 in Section 4.1 required selecting a sample mitigation measure. The population of all grants is first stratified (grouped) by peril. Thus, one such stratum (or group) contains only flood-related mitigation projects. Another contains only mitigation activities related to hurricane winds. The reason for stratifying in this way is that BCRs may differ among these broad categories of mitigation grants, and it is desirable to ensure that several activities in each stratum are represented in the sample. Activities within a stratum do not contribute equally either to total benefit or to total cost. It is likely that a small number of costly activities dominate both cost and benefit.

To ensure reasonable results, this fact should be reflected in the sample. Furthermore, it is desirable that activities of all cost levels are present in the sample. Therefore, mitigation activities within each stratum are sorted by cost. They are binned (grouped in batches of similar total cost) so that the total cost of each bin is approximately equal. Thus, one bin contains a few high-cost projects, another contains many lower-cost mitigation activities. One mitigation activity is then selected at random from each bin. As a result, the sample contains more grants for high-cost mitigation activities than for low-cost ones, and yet still contains at least some grants for low- and medium-cost activities. Mathematical tests performed in the 2005 *Mitigation Saves* study confirm that this approach produces more accurate estimates for the population benefit with less uncertainty than any of several competing alternatives.

Figure 4-3 illustrates the sampling scheme. The red highlighted layer (flood, project, high) defines one stratum within the entire population of all grants. A sample of N projects from the stratum are desired for detailed BCA. First, all the projects in the stratum are sorted by project cost. The projects are grouped in bins. (In the figure, the bins are represented by the stacked boxes on the right and each project is represented by an “o” in the bins.) The first bin (the top one in the upper right of the figure) contains the x most-costly projects, the sum of their costs equaling approximately $1/N$ times the sum of all project costs in the stratum. In the second box, x=3, that is, the next three most-costly grants contribute approximately $1/N$ times the sum of all project costs in the stratum. The project team selects one of these three at random for detailed BCA. (The selected grant is indicated by the red circle.) In the same manner, the figure shows that that the next most-costly five grants also cost approximately $1/N$ times the sum of all project costs in the stratum. The project team selects one of these five at random for detailed analysis. And so on.

Box 4-1. The Impact of Sampling Strategy on Cost-Effectiveness

The 2005 *Mitigation Saves* study considered the approach outlined in Section 4.6 and three others, such as randomly sampling grants with equal probability of picking any grant, regardless of cost. The sampling strategy used here results in the least difference between sample-average BCR and that of the population. It also results in the smallest standard error s in Equation 4-8, e.g., the smallest uncertainty where the true population BCR lies relative to the sample average. Both facts are important because the project’s ultimate goal is to estimate the probability that mitigation is cost-effective, e.g., whether the true, population-wide BCR > 1, as shown in Equation 4-9.

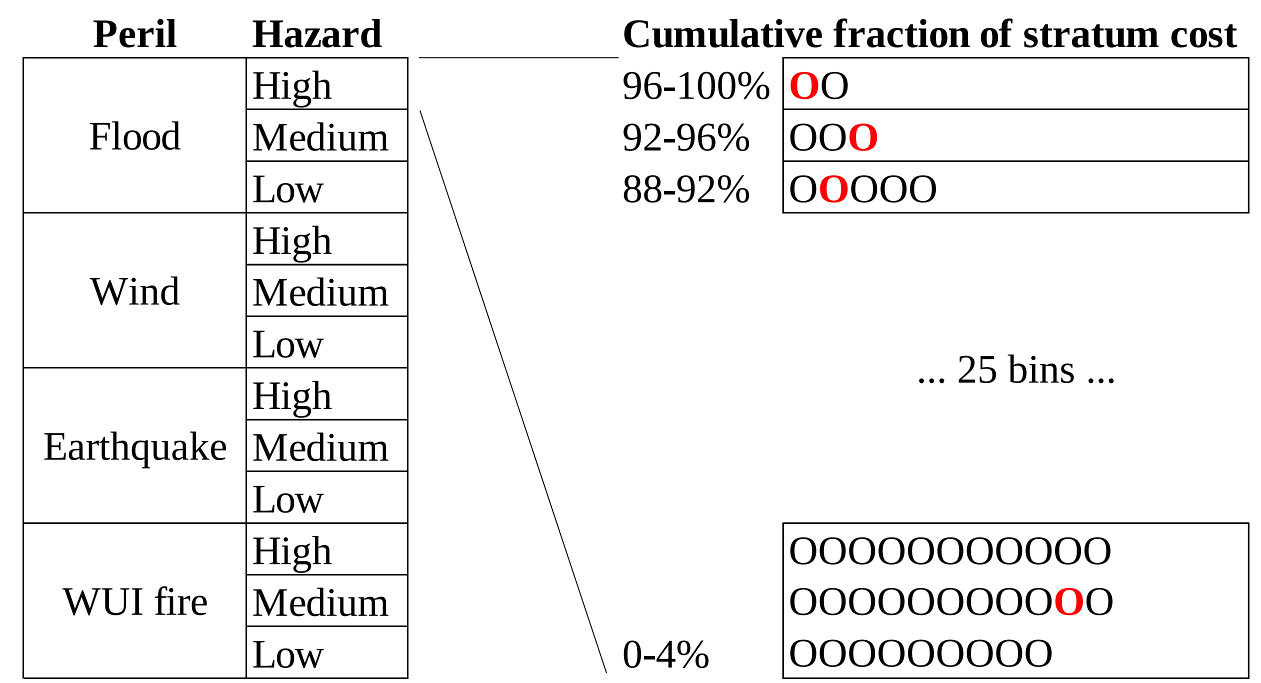

Figure 4-3. Stratified sampling scheme for federal mitigation grants.

4.8 Notes on Riverine Flood Methodology

The project team used different methods to estimate the benefits and costs to mitigate the four perils examined here. In some cases, the project team used Hazus largely as-is. This section presents some details on the largely Hazus-based methodology for estimating benefits and costs of mitigating riverine flooding. See later sections of this chapter for other details, including flood hazard, vulnerability, loss categories, calculation of benefits, and calculation of the BCR.

Figure 4-4 depicts the approach the project team applied to estimate the benefits and costs of exceeding I-Code requirements. The approach seeks to identify elements that were both consistent across geographic locations as well as those that were likely to be more regionally or locally unique. As shown in the figure, the methodology calculated BCR values for elevating single-family homes above I-Code requirements. The effectiveness was determined by calculating the ratio of the amount of saving resulting from the loss avoided due to the elevation of a single-family dwelling (e.g., benefits), to the costs encountered in elevating the dwelling.

Hazus was used to assess building and content losses of single-family homes before and after elevation, as well as to estimate the economic impacts of the elevation activity on the census block in which these homes are located. This Interim Study modeled these impacts both for as-is circumstances reflective of the current built environment in the sample communities, as well as for new construction of single-family dwellings exceeding 2015 I-Code requirements. Benefits were calculated in terms of the amount of loss avoided by elevating new single-family homes to a particular *x* foot above I-Code requirements at the same location of the existing homes. The analysis resulted in estimates of a BCR per additional *x* foot of elevation, accounting not only for building losses but also losses resulting from BI and social impacts resulting from elevating single-family homes as described elsewhere in this Interim Study.

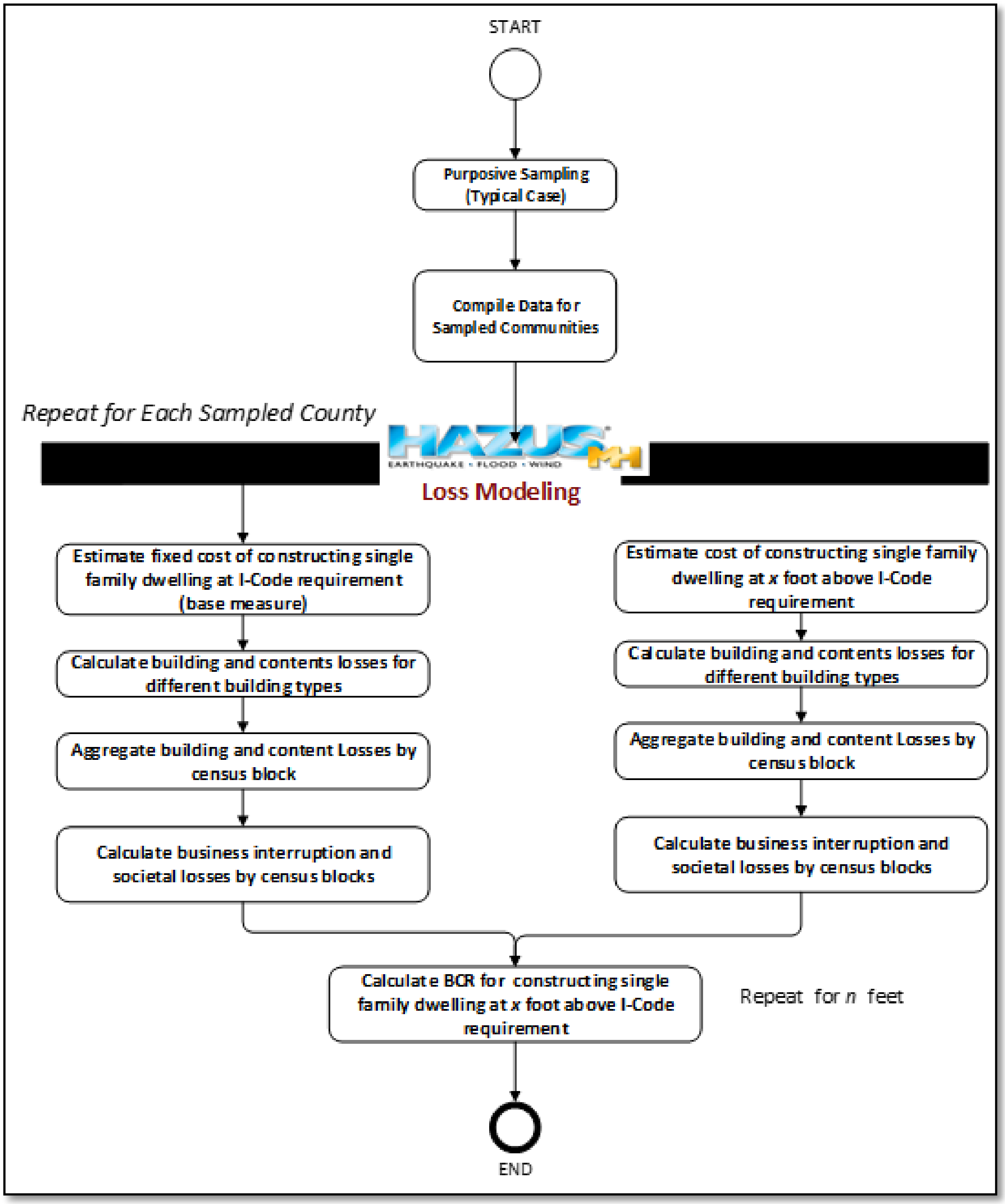

Figure 4-4. Methodology to estimate BCR for designs exceeding I-Code requirements for riverine flood.

Costs. The cost of constructing a new single-family residential dwelling an additional *x* feet above that required by the 2015 I-Codes is calculated using Equation 4-11.

$$C(x) = \alpha + \beta \cdot x + \tau \cdot x$$
(Equation 4-11)

Where,

α = fixed cost of elevating a residential structure of a given type and area

β = incremental cost of elevating a structure of a given type by an additional foot

τ = cost to comply with the Americans with Disabilities Act of 1990 (ADA) for each additional foot of elevation

Equation 4-11 is an approximation. It attempts to capture all significant cost components, but costs may vary between communities. The equation may omit some costs such as code enforcement, if designing to exceed I-Code requirements involves any additional enforcement cost.

Figure 4-5 summarizes the project team's approach to estimating the effectiveness of federal mitigation grants directed to acquisitions of flood-prone structures. As in the analysis of designing to exceed I-Code requirements, the Interim Study used a geographic information system (GIS) with Hazus.

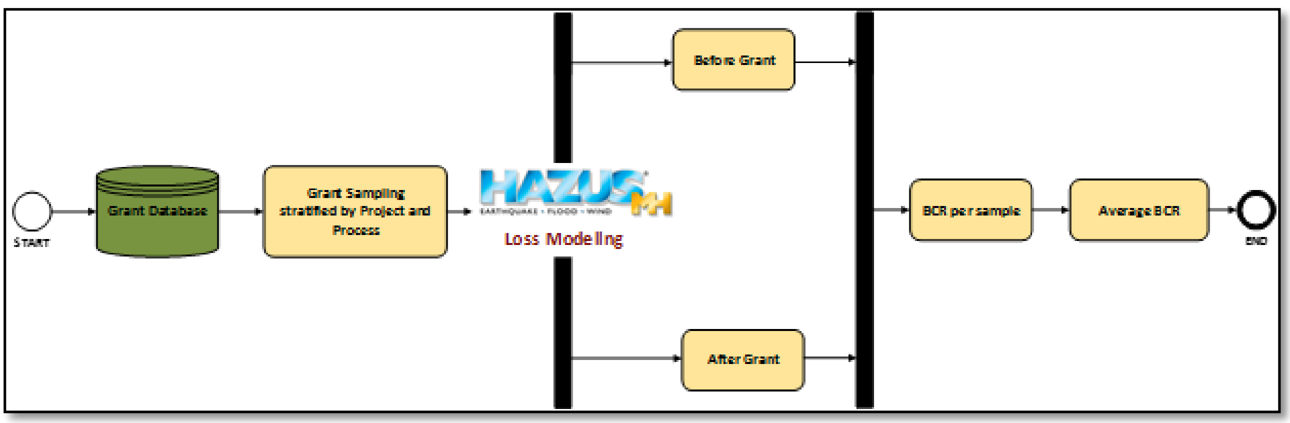

Figure 4-5. Use of Hazus to estimate benefits and costs of federal grants for riverine flood.

4.9 Estimating Exposure

4.9.1 Present Day Exposure

Exposure here refers to the engineering characteristics of the assets at risk: the buildings, utilities, and transportation infrastructure one might enhance with natural hazard mitigation. Engineering characteristics include geographic location, use, structural system, replacement cost, year built, and others.

Grant applications contain most or all of the necessary exposure data for mitigation projects funded by FEMA, EDA, etc. To estimate the costs and benefits of designing to exceed I-Code requirements, one must first estimate the quantity of buildings exposed to natural hazard loss by geographic region, occupancy class, building type, and time of day. Table 4-2 lists several options for how to estimate exposure including the advantages and disadvantages of each. For designing to exceed I-Code requirements for earthquake, the project team used the Hazus inventory created for USGS PAGER, updated to October 1, 2016. For flood and wind, which do not require a nationwide inventory, the project team used superior site-specific information.

Option	Advantages	Disadvantages	Comments
Hazus	Well documented, nationwide scope, fairly authoritative, nationwide inventory tabulated for USGS PAGER project in 2008	2008 data are based on 2002 Hazus data; estimated from proxies of population and employment data	Can approximate growth since 2002 based on state population growth and construction cost indices to account for the increase in square-foot construction costs since 2002.
Population alone	2015 estimates available	No commercial, industrial, government, nonprofit.	
Tax assessor files	Actual enumeration of taxable property	No central resource; costly; diverse formats; often inconsistent valuation procedures; often lacks required parameters	1111 Broadway, Oakland lacks material, LFRS, height, year built, floor area, building replacement cost new, occupants...
OpenStreetMap	Free and detailed outlines of building footprints contributed by the open GIS community. Spatially accurate	Sparse attributes, typically incomplete or not fit for purpose	Appropriate for disaggregating census data or for sampling possible locations when assessing detailed hazards, such as coastal surge or flood
Remote sensing	Efficient use of remote sensing can be used as a stratified sampling technique to apply engineering expertise or observations to an existing hazard data source, such as Hazus, and increase the accuracy of replacement cost and vulnerability assumptions.	Remote sensing technologies require subject matter experts.	Useful when there are limited or broad regional assumptions in mapping occupancy to structural type as well as occupancy to assumed “model building type” for estimating replacement cost.

Table 4-2. Options for exposure data.

Hazus offers the relevant aspects of its U.S. building-stock inventory in a normalized database of 15 tables for each state. To make use of these normalized data, in 2008 Porter compiled the data into a single denormalized table, one table for each state and the District of Columbia (a total of 51 tables). Each table contains one record (one row) for each unique combination of U.S. census tract, Hazus model building type, code level, and Hazus occupancy classification. For each combination, the inventory provides Hazus' default estimate of total building area in square feet, number of occupants at three times of day (2 PM, 5 PM, and 2 AM), building replacement cost (new), and content replacement cost (new).

Census tract was the smallest practical geographic unit of deaggregation for the earthquake risk analysis, owing to limits in file size in Microsoft Access, which was used to create the inventory. (Analyses for other perils such as riverine flood are performed at a census-block or other level. That level of detail is impractical for the earthquake risk analysis, which deals with many combinations of model building type and occupancy class in each census area.) U.S. census tracts generally have a population size between 1,200 and 8,000 people, with an optimum size of 4,000 people. They can be geographically large or small depending on population density. Greater population density means smaller tracts. Miami-Dade County, Florida, for example contains 360 tracts with an average area of approximately 14 square kilometers (USCB 2010). Figure 3.5 shows the size of a census tract in downtown Oakland, California. The blue lines delimit census tracts. The tract with a blue dot in it contains approximately 32 city blocks. The blue dot represents the geographic center (called the centroid) of the tract. If one treats all the people and property in the tract as if they were all at the centroid, one sacrifices little accuracy in estimating seismic hazard, because the centroid is on average less than 250 meters from any given building in the tract. In suburban and rural communities, the distance is greater, but the value exposed is also lower and the error contributes less to the estimate of societal risk. The usefulness of census-tract-level information varies by peril: it is most useful for earthquake and perhaps tornado, least useful for riverine and coastal flood.

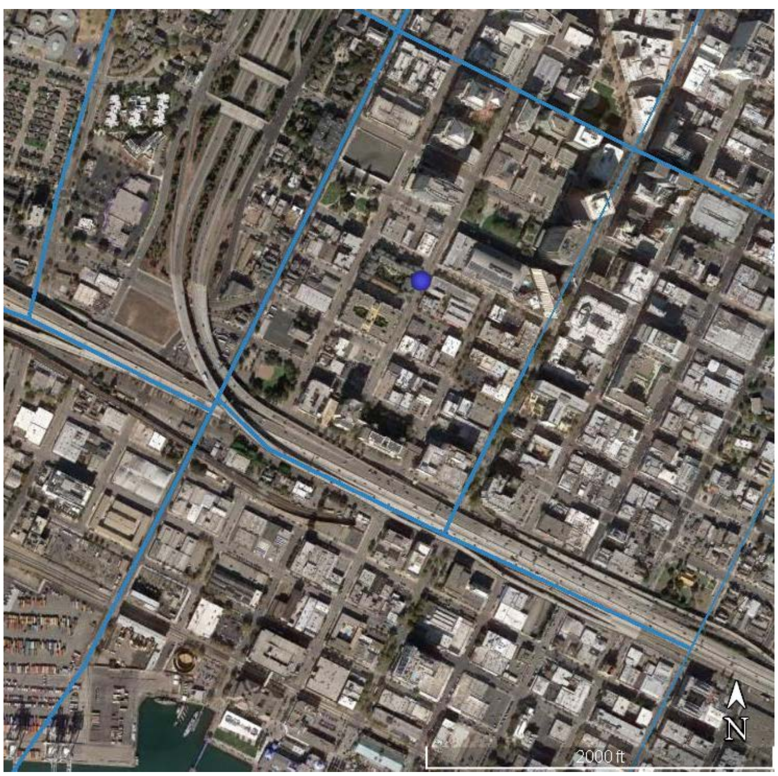

Figure 4-6. Census tracts near downtown Oakland, California.

WUI exposure has been mapped for the conterminous United States at the census block level (Martinuzzi et al., 2015a, 2015b). This dataset provides information on housing units and population in each census block and is the basis for analysis of assets at risk. Analysis of all census blocks in the conterminous United States was computationally infeasible, so the project team did analysis at the census block level for four counties (population in millions in parentheses): Los Angeles County, California (10.12), Alameda County, California (1.61), Ada County, Idaho (0.43), and Atlantic County, New Jersey (0.28). These four counties were selected as spanning the range of WUI fire hazard severity—Ada County has some of the highest BPs in the entire nation, parts of Los Angeles County are also high fire hazard with a very large population, Alameda County similarly is at high risk and was the site of the 1991 East Bay Hills fire, perhaps the largest WUI fire loss in modern history; Atlantic County is more typical of moderate fire hazard in the eastern United States.

The project team analyzed one single-family dwelling prototype in each census block (e.g., all housing units in the WUI are assumed to be this prototype). The project team recognized that there are many other buildings and physical assets at risk within the WUI, beyond the single-family dwelling prototype—not even all housing units are single-family dwellings. However, the analysis is confined to this one prototype because 1) nationwide, it is by far the most prevalent building type within the WUI; 2) many other building types in the WUI (e.g., small stores, offices, places of business in general, commercial strip malls, schools and places of assembly) are often of wood frame construction, and do not differ significantly from the prototype with regard to fire vulnerability; 3) even non-combustible construction when subjected to WUI fire attack, if undefended, will, in most cases, burn to destruction; 4) the focus of the IWUIC is clearly on wood frame construction, for which the prototype is the most common example. Beyond buildings, other assets in the WUI fall broadly into two categories: 1) human-made, such as roads, bridges, tunnels, airports, utilities, larger infrastructure such as electric transmission facilities, water supply reservoirs, etc. None of these are the subject of the IWUIC, and their consideration is beyond the scope of this project; 2) natural environmental assets, including flora and fauna. While of enormous value, again these are not impacted by the 2015 IWUIC and their consideration is beyond the scope of this project.

Hazus model building types for earthquake risk analysis are listed in FEMA (FEMA 2012e) Table 5.1, among other places. Model building types generally classify buildings by structural material (mostly wood, reinforced concrete, steel, or masonry), lateral force resisting system (generally shearwall, frame, or bearing wall), and height class (1-3 stories, 4-7 stories, or 8+ stories). Hazus classifies a building as having one of four code levels: pre-code, low code, moderate code, or high code, generally referring to the degree to which the code in force at the time of construction specified sufficient lateral strength and structural detailing requirements to ensure a complete load path, among other goals. Hazus also allows for three more classes of special construction, called “above-code” in FEMA (2012e) but more accurately referring to buildings that would have been built according to code requirements for hazardous or essential facilities (risk category III or IV, in the terminology of the ASCE [2010]). See FEMA (2012e) Table 15.1 for Hazus occupancy classes; it lists 33 classes, generally subcategories of residential, commercial, industrial, agriculture, religion, government, and education.

The 51 inventory tables (one for each state plus the District of Columbia) were originally compiled in 2008 and reflect the inventory that the Hazus developers provided in 2002. The population has grown since 2002 and construction prices have increased. One can reflect these increases as follows: Factor square footage and number of occupants by a population growth factor F_1 to account for population growth on a state-by-state basis from January 2002 to October 2016 (the date of the beginning of the present project). See Equation 4-12. Factor building and contents replacement costs by both the population growth factor F_1 and a factor F_2 to account for both population growth and the increase in per-square-foot construction costs over time. See Equation 4-13. In the equations, *P*(year) denotes the U.S. Census Bureau's population estimate as of the stated year (USCB 2004). The factor 14.75/13 is used to linearly extrapolate from January 1, 2002 to October 1, 2016. The term *C*(year) denotes RSMeans' 2015 national 30-city average historical city cost index (CCI) as of the stated year. RSMeans is the leading publisher of U.S. construction cost data. Its national 30-city CCI reflects an estimate of the nationwide average growth in construction costs (RSMeans n.d.).

$$F_1 = \frac{P(2015)}{P(2002)} \cdot \frac{14.75}{13.00}$$
(Equation 4-12)

$$F_2 = \frac{C(2015)}{C(2002)} \cdot \frac{14.75}{13.00}$$
(Equation 4-13)

Recall that the inventory of buildings representing code-compliant design is to be modeled as if designed to the 2015 IBC, but using each state's local mix of lateral force resisting systems, building heights categories, and occupancy classes. To reflect that mix, the project team modeled the code-compliant inventory in each state using the distribution of the most recent construction as reflected by the highest code level in that state's inventory. In cases where even that most-recent design level includes obsolete building types such as unreinforced masonry bearing walls, one can change obsolete types to similar but non-obsolete types. For example, the project team changed all midrise unreinforced masonry bearing wall buildings to high-code reinforced masonry buildings with rigid diaphragms. To reflect designing to exceed 2015 I-Code requirements, the analysis uses the same mix of structural systems, heights, and occupancies, but with greater strength and stiffness as discussed later.

Content and stock damage are also modeled, because their damage will be affected by the designing to exceed I-Code requirements. Their replacement-cost values are estimated as a factor of building replacement cost, using the same factors assumed by the Hazus developers.

Note that for purposes of evaluating benefits of designing to exceed I-Code requirements, the project team mapped BCR on a geographic basis (e.g., b_i/c_i of Equation 4-7), e.g., without multiplying by total expenditures (E_i in Equation 4-3). The exposed values, their geographic locations, and their change over time only matter when one estimates the aggregate benefits and costs (*B* and *C* of Equation 4-6). The method to project population growth and spread is discussed next.

4.9.2 Creating a Proxy Portfolio for Designing to Exceed I-Code Requirements for Riverine Flood

The project team used a purposive sampling technique of typical cases of communities that represent common floodplain conditions and residential structures found in riverine flooding across the United States. The word *typical* here implies that the results and conclusions are illustrative for all communities in the United States that meet the characteristics of the urban and rural communities analyzed in this Interim Study.

The decision to apply a purposive sampling approach to select target communities was justified by the following:

- The existence of a relatively small number of geographic areas (sample areas) where detailed data are available and where the built environment is diverse enough to allow for the exploration of various elevation scenarios; and
- A recognition that both the nature of the analysis performed in the Interim Study and the generated benefit and cost functions per foot of elevation require close consideration for specific flood events in specific communities.
- Use of a regression model to generalize results of the analysis to similar characteristics across the United States (see Section 3.1.1. of this Interim Study).

The selection of sample communities was based on a number of different factors. Among these were:

- House size
- Foundation types: open (crawlspace/pier foundation) versus closed (slabs)
- Construction cost
- Flood hazard conditions (1% versus 0.2% annual chance of flooding)

The following parameters likely matter most to the cost-effectiveness of designing to exceed I-Code requirements for riverine flood:

- Footprint area
- Number of stories
- Foundation type (piers or piles, open or closed)

The project team evaluated the cost-effectiveness of designing to exceed I-Code requirements for riverine flood for four building sizes (Table 4-3), six foundation types and five elevations (Table 4-4), and four geographic regions (Figure 4-7). The four regions were Monroe and Fulton Counties in Georgia, and Elkhart and Allen Counties in Indiana. Monroe County is rural, while the rest are pronominally urban. All the buildings are single-family dwellings (RES1 in Hazus nomenclature). The four counties have different distributions of house size (in terms of stories and total floor area) and foundation type (open or closed), as summarized in Table 4-5. All the houses are located in the 500-year (0.2% probability per year) flood area. Only rural Monroe County, Georgia has open-foundation houses in the 0.2% annual chance flood area; houses in the 0.2% annual chance flood area in the more-urban counties all have closed foundations. Section 5.1.1 further presents regression models the project team developed to generalize the results of the analysis.

Building size	Length (ft)	Width (ft)	Stories	Footprint (sf)	Floor area (sf)
1	50	30	1	1,500	1,500
2	50	30	2	1,500	3,000
3	60	40	1	2,400	2,400
4	60	40	2	2,400	4,800

Table 4-3. Four building sizes used to determine BCRs for riverine flood.

Flood hazard zone	Foundation types	Lowest floor elevation (ft)
A	Timber pile Concrete pile Masonry pier 8" masonry pier 12" masonry pier Fill and slab-on-grade	BFE +1 BFE +2 BFE +3 BFE +4 BFE + 5

Table 4-4. Foundation and elevations used to determine BCRs for riverine flood.

Figure 4-7. Locations used to determine BCRs for riverine flood.

County	Open foundation				Closed foundation			
	1 story 1500 sf	2 story 3000 sf	1 story 2400 sf	2 story 4800 sf	1 story 1500 sf	2 story 3000 sf	1 story 2400 sf	2 story 4800 sf
Allen, IN	0	0	0	0	97	49	41	6
Elkhart, IN	0	0	0	0	82	59	223	48
Fulton, GA	0	0	0	0	195	161	99	168
Monroe, GA	15	6	9	2	1	0	1	0

Table 4-5. Portfolio of foundation type (open or closed) and house size (stories and total area) by county, used to determine BCRs for riverine flood.

Workflow. The project team applied a GIS to carry out the following analytical steps. (The steps mix the tasks of developing a sample inventory and characterizing hazards.)

Step 1: Develop depth grids. The project team used Hazus to generate two depth grids: one grid showing depths at each grid point in each county with a 1% exceedance probability in 1 year (100-year mean recurrence interval) and another showing depths with 0.2% exceedance probability in 1 year (500-year mean recurrence interval). Recall that the 2015 I-Codes require the first floor elevation be at least BFE + 1, e.g., 1 foot above the depth with 100-year mean recurrence interval.

Step 2: Classify depth grids based on water level. The project team classified depth grids for the 1% annual chance and 0.2% annual chance year return periods developed in Step 1 based on water level (e.g., flood inundation level). The classification resulted in two zone categories: shallow water or deep water. The project team classified cells with depth less than the median as lying in the shallow-water zone, labeled “zone 1” for brevity. The team classified cells having depth greater than the median as lying in the deep-water zone, or “zone 2” for short.

Step 3: Create a proxy building inventory based on the real building stock. Each house in the real building stock of the four sample counties is unique. See Section 4.1.4 for a description of the inventories. To make the BCA tractable, the project team simplified the real building stock by imagining that new buildings of a limited number of designs were to be built in place of the existing ones in the 1% annual chance flood plain. Every building in the real inventory was mapped to its closest approximation in Table 4-3, first considering number of stories, then by nearest total square footage. For example, if an actual single-family dwelling had 1 story, it was mapped to either size 1 or 3, e.g., either a 1-story, 1,500-square-foot house or a 1-story, 2,400-square-foot house. If the real house had a total floor area of 1,450 square feet, it was mapped to (in a sense, replaced by) the 1-story, 1,500-square-foot house (size 1 in Table 4-3), for purposes of BCA. That is, the project team estimated benefits and costs for a new size-1 house built at the location of the real house.

Step 4: Assign foundation types to the proxy building inventory. The project team assigned each building in the proxy portfolio to one of two foundation types: open or closed, based on which Hazus foundations type the real building has, as shown in Table 4-6. With four building sizes and two foundation types among the proxy buildings, each real building maps to one of 8 models, labeled A through H, as shown in Table 4-7.

Step 5: Associate each house with a grid cell and thus a depth zone: shallow (zone 1) or deep (zone 2). With four possible building sizes, two possible foundation types, and two possible depth zones, the project team mapped each real house in the four sample counties to one of 16 cases, that is, combinations of size, foundation type, and depth zone, listed in Table 4-8.

Step 6: The project team used 16 different cases shown in Table 4-8 to randomly stratify census blocks in the four sample counties to model the effectiveness of building new single-family dwellings to greater elevation. The team selected these census blocks by first determining the dominant building classification in each census block; and second by ensuring that each of the four counties had as many as possible of the 16 cases represented.

Step 7: Update the Hazus GBS and Hazus UDF inventories. The project team updated the Hazus GBS inventory with all buildings located in the stratified census blocks. The project team updated the Hazus UDF facility inventory only with the single-family dwellings contained within the stratified census blocks. The project team used the Hazus GBS inventory to determine BI values within the impacted area considering all occupancy classes rather than just single-family dwellings (RES1). The team used the Hazus UDF inventory to derive all other impacts: building damage, content damage, etc. Table 4-9 provides the number of buildings included in the final dataset modeled for each case and county.

Real house has this foundation type	Proxy house was assigned this type
Crawl space	Closed
Basement	Closed
Slab	Closed
Pier	Open
Pile	Open
Fill	Closed
Wall	Closed

Table 4-6. Assigning foundation type to riverine flood proxy portfolio.

Model	Description
A	Size 1, open foundation
B	Size 1, closed foundation
C	Size 2, open
D	Size 2, closed
E	Size 3, open
F	Size 3, closed
G	Size 4, open
H	Size 4, closed

Table 4-7. Assigning model label to riverine flood proxy portfolio buildings based on size and foundation.

Case	Description	Case	Description
A1	Size 1, open foundation, shallow	A2	Size 1, open foundation, deep
B1	Size 1, closed, shallow	B2	Size 1, closed, deep
C1	Size 2, open, shallow	C2	Size 2, open, deep
D1	Size 2, closed, shallow	D2	Size 2, closed, deep
E1	Size 3, open, shallow	E2	Size 3, open, deep
F1	Size 3, closed, shallow	F2	Size 3, closed, deep
G1	Size 4, open, shallow	G2	Size 4, open, deep
H1	Size 4, closed, shallow	H2	Size 4, closed, deep

Table 4-8. Assigning a case identifier to riverine flood proxy portfolio buildings based on size, foundation, and depth.

Case	Number of Buildings			
	Monroe County, GA	Fulton County, GA	Elkhart County, IN	Allen County, IN
A1	33	0	0	0
B1	0	201	105	62
C1	16	0	0	0
D1	0	120	85	44
E1	10	0	0	0
F1	5	98	106	58
G1	0	0	0	0
H1	0	280	61	8
A2	9	0	0	0
B2	0	118	149	6
C2	10	0	0	0
D2	0	57	55	35
E2	13	0	0	0
F2	0	45	104	20
G2	9	0	0	0
H2	0	204	61	0
Total	105	1,123	726	233

Table 4-9. Number of buildings by county and size-foundation-depth case in sampled census blocks of the riverine flood proxy portfolio.

4.9.3 Estimating Building Exposure for Riverine Flooding

To estimate the pre-mitigation building stock for regions subject to riverine flooding, particularly to analyze federal grants, the project team combined the Hazus GBS data with a user-defined facility inventory. The user-defined facility inventory was updated to represent the pre-mitigation location and conditions of the structures acquired by each grant. Where possible, the locations of these structures were based on the information in the grant database. However, in some cases, it was necessary to adjust these locations slightly because they either were not located in the Hazus generated depth grid or they were not located within one of the dasymetric census block boundaries.

When this adjustment was made, the project team moved the locations of the points as little as possible so that they fell within the 100-year flood inundation area and within a dasymetric census block boundary. In addition, the team chose the locations of moved structures to ensure that the depth of water in the 100-year flood exceeded the first-floor elevation of the building. The 1% annual chance event was selected because it was assumed that acquisitions were unlikely as a results of lesser flooding events.

To estimate post-mitigation building stock, the project team duplicated the pre-mitigation inventory, changing it to reflect the grant activity, e.g., by removing buildings acquired through the grant. Tables specifically modified included those reporting square footage, building count, dollar exposure and content exposure.

4.9.4 Estimating Building Exposure for Coastal Inundation

Coastal inundation presents a special problem for BCA, so a special approach is required to deal with it. The project team considered several options for constructing the building exposure database used to model the effects of designing new coastal buildings to exceed building code requirements for elevation. Each has advantages and disadvantages.

Typically, regional studies rely on census or regional data to approximate the building stock. Such an approach has a number of severe disadvantages. Exposure to storm surge changes throughout a coastal census tract or block with site elevation, coastal distance, and other local topographic and bathymetric features. Hazard can vary over distances of tens of meters, much smaller than a census tract, block group, or even census block, so building locations within the block or tract matter a lot. Coastal homes tend to be irregularly distributed within a block or tract, and are more likely to be clustered around streets that follow the coast, rather than close to the water on the beach. Census blocks extend past the coast, so an automated approach to estimating building locations based solely on census block boundaries and numbers of people or buildings in the census block is likely to estimate unrealistic building locations. One would likely estimate building locations as being in the surf, exaggerating the hazard and grossly under- or overestimating BCRs.

Local studies may use site-specific building data in the form of street addresses. While it can produce better accuracy than distributing building within census boundaries, geocoding addresses can also misrepresent building locations enough to matter to a BCA. Automated geocoding can result in estimated locations that are evenly offset (set back) from the street, but the true setbacks can differ significantly from a geocoding program's default setback, potentially by tens of meters, enough to produce large errors in hazard.

OpenStreetMap (OSM) offers a third option: building footprints (OSM, 2017). OSM building footprints allow sampling of actual site-specific building locations more accurately than geocoding and far more accurately than census data. Its disadvantage is that with greater accuracy comes greater computational burden. Weighing the advantage of accuracy against the computational burden, the project team opted to estimate coastal building exposure using OSM building footprints, and dealt with the computational burden as described next.

Approximately 30,000 buildings from Texas to Maine intersect (lie within or touch) the FEMA NFIP V- or VE-zones (FEMA, 2014d). For purposes of estimating the cost-effectiveness of designing new buildings to exceed code requirements, imagine that new buildings are built to replace existing ones, always at the same location. A total pf 30,000 buildings in V- and VE-zones were available for processing, though building footprints were not provided for every building. To make the problem computationally tractable, the project team randomly selected up to 1,000 building footprints per each of seven states, for a total of 7,000 locations. The project team extracted the latitude and longitude of the centroid of each of these 7,000 footprints and performed BCA for a new house located at that point.

4.9.5 Number of People and Households Based on Number of Buildings

In some cases (especially riverine flooding), the project team knew the number of residential buildings and needs to estimate number of occupants and number of households. The project team estimated number of occupants using Table 4-10. The table lists the residential occupancy classes examined for riverine flooding using the Hazus notation. With the number of occupants determined, the project team estimated number of households by dividing number of residential occupants by 2.5 people per household.

Occupancy	Description	Number of occupants
RES1	Single-family dwelling	2.5 people per building
RES2	Manufactured housing	2.5 people per building
RES3A	Duplex	5 people per building

Table 4-10. Estimated building occupancy for riverine flooding.

4.10 Estimating Hazard

In the present context, hazard refers to a relationship between environmental excitation and exceedance frequency in events per year. Environmental excitation refers to the forces or other loading conditions that the natural environment imposes on infrastructure. Table 4-11 lists hazard measures and sources. Details are provided in the following sections.

Peril	Measures, units	Source
Flood	Depth (A-zone), m Momentum flux (V-zone), m^3/sec^2	Hazus
Hurricane wind	10-meter 3-sec peak gust velocity (m/sec)	ASCE 7-16[(a)]
Tornado wind	N/A. See Section 4.10.4.	NWS
Storm Surge	10-meter 3-sec peak gust velocity (m/sec)	ASCE 7-16 (ASCE, 2017)
	MOMS (Maximum of MEOWs (Maximum Envelope of Water), Category 1-5, ft of surge height.	NOAA 2013 SLOSH modeling (NOAA NHC, 2014)
	Projected sea level rise (cm) given GMSL scenario. Posted by tide gauge location.	NOAA Technical Report NOS CO-OPS 083 (Sweet, et al., 2017)
	Sea level rise on land given sea level rise, ft	NOAA SLR Viewer (NOAA, 2017)
	Extent of "V" or "VE" zone.	FEMA Flood Maps (FEMA, 2014d)
	Elevation, feet	USGS (USGS, 2017)
Earthquake	Sa(0.2 sec, 5%), g or Sa(1.0 sec, 5%), g, both geographic mean of two orthogonal directions.	Petersen et al. (2014); Vs30 from OpenSHA.org site data app at tract geographic centroid (preferred value), F_V from 2015 NEHRP Recommended Provisions (FEMA 2015d).
Fire	(1) Burn probability (2) Flame intensity level	(1) Finney (2011); Short (2016) (2) Byram (1959); Scott (2013)

(a) 2016 represents the best available hazard information.

Table 4-11. Hazard measures and sources.

4.10.1 Estimating Riverine Flood Hazard

A flood risk model has three key components: the delineation of the flood hazard; the exposure (buildings, population, etc.); and the methodology that relates the hazard to the exposure to derive economic and social impacts. These components can be compared to the legs of a chair. If one of the legs is weak the chair collapses or, in the case of a model, the model produces output that may lack credibility.

As discussed in Chapter 3, the lack of detailed flood hazard and exposure data was a limitation of the flood analysis in the 2005 study. In addition, at the time that study was completed, there were limited options for using GIS tools to analyze flood impacts. The lack of data limited the potential value of technologies such as Hazus. The present Interim Study applied improved modeling capabilities, and integrated data resources that were unavailable for the 2005 study.

The project team determined the majority of loss calculations in Hazus by applying depth-damage functions to evaluate the relationship between exposed buildings and other community assets, and a flood depth grid that defines the extent and severity of the hazard. Users can either create a depth grid with Hazus or they can provide their own depth grid. Since the 2005 study was completed, depth grids have been developed for a number of communities across the United States. FEMA's Risk MAP program has been especially helpful in this as it has led to the development of new information, including depth grids in some cases, to help communities understand and mitigate the impact of flood hazards.

The project team evaluated the availability of depth grids from Risk MAP and other sources for this Interim Study but determined that none were available within areas for which other critical study input such as building inventory was available. Accordingly, the project team used Hazus Release 3.2 to generate the depth grids needed for above-code measures as well as federal mitigation grants. While Hazus may deliver less-precise depth grids than those produced with more robust engineering tools and methods, they seem adequate for this Interim Study.

To support the analysis of designing to exceed I-Code requirements, the project team used both 1% annual chance return period (1% annual chance) and 500-year return period (0.2% annual chance) depth grids for each of the four counties included in the Interim Study (see Section 4.9.2) using the Hazus suite-of-return-periods option. These were based on a 1 arc-second digital elevation model and a 5-square-mile drainage threshold. To study the cost-effectiveness of federal grants, the project team sometimes used a drainage threshold of less than 5 square miles, but always large enough to estimate flood hazard at the location of the mitigated building.[11]

4.10.2 Estimating Storm Surge Hazard

Nobody offers regional probabilistic coastal surge hazard data. One must estimate it. In summary (details follow), the project team used worst-case evacuation maps that show evacuation zones for each of several Saffir-Simpson categories. The project team scaled the estimated surge heights to match local flood studies, and estimated the mean recurrence interval from wind speed maps. The list below provides a brief explanation of each dataset, followed by a description of the steps to estimate probabilistic storm surge elevation:

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[11] For details on how Hazus generates depth grids, see FEMA (2011b).

Step 1: Flood maps for NFIP (FEMA, 2014d). FEMA digital flood maps provide the extent of analysis where a significant risk from storm surge justifies building above the required code. These data also provide a key indicator of the BFE: 6 feet above ground elevation at the landward edge of the delineated zone according to FEMA P-55 (2011a). This provides a method to estimate the BFE regionally. The project team downloaded data for all states in the conterminous United States exposed to coastal storm surge. Although most areas have digital FEMA flood maps available, South Carolina does not have data available.

Step 2: Preliminary design wind speed maps from ASCE 7-16 (ASCE 2017). Design wind speeds are used to model the probable return interval of hurricanes corresponding to the Saffir-Simpson hurricane wind scale. The project team acquired the data just before general release. The data are generally consistent with ASCE 7-10, but include the 3,000-year mean recurrence interval to characterize rare storms.

Step 3: MOMs surge heights by Saffir-Simpson hurricane wind scale from NOAA (NOAA NHC, 2014). Emergency managers use the surge height estimates primarily for evacuation purposes. The surge heights also provide a consistent nationwide data source for assessing coastal surge hazards from hurricanes. NOAA delivers the data in separate GIS layers, each representing the maximum probable surge heights for a given Saffir-Simpson hurricane wind scale category. Using the ASCE 7-16 wind speeds (ASCE, 2017), one can assign each storm category a mean recurrence interval given the wind hazard at the coast. (This process is discussed below.) The project team adjusted the maximum surge height regionally to represent a mean surge elevation using the FIS performed for the NFIP (FEMA, 2003, 2006a, b, 2007b, c, 2008c, d, 2009a, b, 2012a, b, c, 2013a, 2014b, c). The project team used approximately a dozen FIS studies to scale the MOMs and applied scaling factors for each of three regions: (1) Gulf states including western Florida; (2) eastern Florida up the coast to South Carolina, and (3) from North Carolina northward.

Step 4: USGS National Elevation Dataset (USGS 2017). Ground elevation at a given site combined with the location nearest to a border between a V- or VE-zone in the FEMA flood maps (FEMA 2014d) provide the ground required to estimate the BFE at each location.

Step 5: NOAA global and regional sea level rise scenarios for the United States (Sweet et al. 2017). NOAA estimates sea level rise for gauge locations globally. The project team chose four scenarios: low, intermediate-low, intermediate-high, and extreme to represent a low, moderate, high, and extreme sea level rise scenario, and assigned the regional sea level rise by creating Theisen polygons surrounding each location and assigning the closest gauge. The result is a map of likely regional sea level rise though time for off-shore point locations. Intermediate-low was chosen as the mean scenario, corresponding to global rise of 50 cm, ± 2 cm (approx. 20 in. ± 0.8 in.).

Step 6: NOAA sea level rise (NOAA 2017). In tandem with the Sweet et al. (2017) data, the NOAA sea level rise spatial datasets provide projected sea level rise on shore and on land for six scenarios representing 1 to 6 feet of inundation. The estimates do not model complex coastal impacts or erosion.

Recall from Section 4.9.2 that the analysis uses 7,000 sample locations from the OSM (2017) footprint data set. The project team estimated probabilistic hazard at the centroid of each sampled footprint, as follows:

Step 1. Estimate BFE. Estimating the BFE required two elevation levels: the elevation at the centroid of the OSM footprint (E_1) and the elevation at the inland location representing the transition from the V- or VE-zone (E_2) (FEMA 2011a). The project team did not analyze the cost-effectiveness of building above coastal A-zones because these zones are not identified in the NFIP data. The project team determined the location at which to estimate E_2 using a custom Python application that accesses a PostGREsql database developed for this purpose. One can then calculate BFE as shown in Equation 4-14. See Step 5 below for the meaning of the factor of 1.55.

$$BFE = (E_2 + 3.85 - E_1) \cdot 1.55$$

(Equation 4-14)

Step 2: Estimate mean recurrences interval using Saffir-Simpson category. NOAA provides MOMs surge estimates (NOAA NHC, 2014) for category-1 to category-5 storms, but what is their mean recurrence interval? The ASCE 7-16 wind speed data (ASCE 2017) provides wind speeds with each of seven mean recurrence intervals. The project team used the latter to estimate the former, as follows. Let i denote an index to seven pairs (x_i, y_i) of data, where x_i denotes 3-second peak gust velocity at 10-meter elevations and y_i denotes mean recurrence interval in years. The project team extracted seven such pairs from the ASCE 7-16 wind speed maps for each location of interest. The pairs have common y values: y_1 = 10 years, y_2 = 25 years, etc., at each location. The other y values are 100, 300, 700, 1,700, and 3,000 years. Let x denote the wind speed at the midpoint between lower and upper bounds of the peak gust velocity for each Saffir-Simpson category. The project team estimated y, the mean recurrence interval for each Saffir-Simpson intensity at each location by linear interpolation within (x_i, y_i) data, e.g., Equation 4-15, where x_0 refers to the maximum x_i such that $x_i \leq x$, x_1 refers to the minimum x_i such that $x < x_i$, and y_0 and y_1 are the y-coordinates of x_0 and x_1, respectively.

$$y = y_0 + (x - x_0)\frac{y_1 - y_0}{x_1 - x_0}$$

(Equation 4-15)

Step 3. Estimate surge height. For each location, use GIS to extract the surge elevation by Saffir-Simpson category from the NOAA MOMs (NOAA NHC 2014). Given that NOAA MOMs provide a worst-case scenario for evacuation purposes, these estimates need to be adjusted to represent mean surge elevation. Several FIS studies (FEMA 2003, 2006a and b, 2007b and c, 2008c and d, 2009a and b, 2012a, 2013a, 2014b and c) provide surveyed data suitable for adjusting the expected surge elevation given a return interval. For each study, the project team entered surge estimates for approximately 5 locations into a GIS database and extracted the estimated storm surge by Saffir-Simpson category. For each Saffir-Simpson category, analysts used linear interpolation to assign a return interval using the same method described in Step 2 above. The result was two datasets: MOMs surge height versus mean recurrence interval and FIS surge height versus mean recurrence interval. The project team took the FIS as a mean estimate of surge and MOMs as an upper bound. The ratio of the latter to the former at a given mean recurrence interval estimates the degree to which MOMs surge heights are greater than best estimates. The project team used the ratio to de-amplify MOMs surge heights to best estimates. Figure 4-8 provides an example for Pinellas County, Florida (FEMA 2009b).

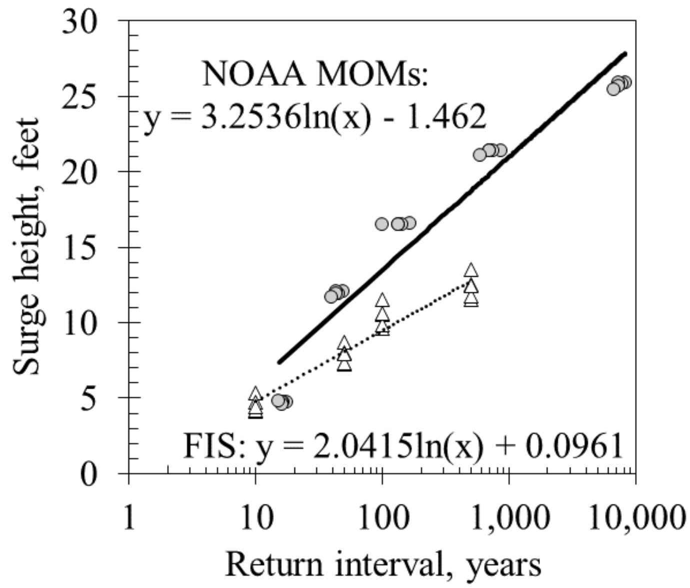


Figure 4-8. Sample data for adjusting NOAA MOMs surge elevations (NOAA NHC, 2014) to FEMA FIS estimates, Pinellas County, Florida (FEMA, 2009b).

Step 4. Accounting for sea level rise. Sea level rise is a cumulative hazard that impacts coastal surge elevation as well as the effectiveness of mitigation. For each location and for each sea level rise scenario, the NOAA global and regional sea level rise scenarios (NOAA 2017) provide an estimated height in feet (data set 5, above). Given that elevation in feet, the project team added the corresponding NOAA projected sea level rise (data set 6) to the NOAA MOMs (NOAA NHC 2014). To account for sea level rise, the project team divided the 75-year projected lifespan of a building into five 15-year intervals and assessed benefits at the midpoint (2025, 2040, 2055, 2070, 2085). Future benefits for distant time slices were discounted accordingly.

Step 5. Accounting for wave height. MOMs (NOAA NHC, 2014) estimate stillwater surge elevation. After adjusting these values and added sea level rise, the project team multiplied the values by 1.55 to account for wave height. Hence the factor of 1.55 in Equation 4-13.

Step 6. Removal of benefits for locations under water due to sea level rise alone. In cases that the sea level rise reaches the building footprint, no benefits are realized from that year on. That is, if a house is still dry between high and low tide given a sea level rise estimate, there may be benefits to mitigation. However, if the house is not dry between high and low tide, benefits are no longer realized. The BCR excludes any benefits to buildings that cannot be reached because the surrounding land is regularly flooded.

Step 7. Estimation of surge depth. The project team assessed damage using the value of projected surge depth above lowest floor elevation. For records not removed under Step 6 above, this is the difference between the value from Step 5 and the value in Step 1, modified to account for additional elevation above the BFE.

4.10.3 Estimating Hurricane Wind Hazard

The project team used the wind speed maps from ASCE 7-16 (ASCE 2017). These maps, which were delivered to the project team before general release, show wind speeds for different return intervals. For this Interim Study, the area of analysis covers all locations with a wind speed with 7% exceedance probability in 50 years exceeds 110 mph. While the 115-mph contour is the lower bound for hurricane-prone regions per the IRC; the 110-mph contour from ASCE 7-16 was also included in this independent review to assess cost-effectiveness of mitigation at lower wind speeds, and thus includes some of the high wind and mitigation options available in the IBHS FORTIFIED Home High Wind program subject to straight-line wind (IBHS 2015). The analysis does not consider mitigation benefits for those structures subject to tornado wind. The analysis (shown in section 5.1.3) produces favorable benefit-cost ratios for the 110-mph contour, thus the reason for inclusion in the Interim Study. This choice refers to the basic wind speed used for design of ordinary buildings, risk category II in the sense of ASCE 7-10. The wind speed with a 7% exceedance probability in 50 years corresponds to a 700-year mean recurrence interval.

Assessing BCR for this wide area required geographic simplification. There are thousands of combinations of wind speeds by return interval throughout the entire area. Two places with 700-year wind speed is 115 mph can have different values of wind speed with a different mean recurrence interval. It turns out however that, considering places with the same 700-year wind speed, the variability of the wind speeds associated with the other mean recurrence intervals was quite small: their standard deviation less than 5 mph. The project team therefore estimated exposure by 700-year wind speed, and estimated a population-weighted average of the wind speed with other mean recurrence intervals, as described next. Simplifying the hazard in this way allows for a more sophisticated assessment of options to designing to exceed I-Code requirements associated with the IBHS FORTIFIED Home Hurricane and High Wind program (IBHS 2012, 2015).

When designing most ordinary buildings to meet the 2015 IBC, engineers start with a so-called basic wind speed that has approximately a 7% probability of exceedance in 50 years, which corresponds to an annual exceedance probability of 0.00143 and a mean recurrence interval of 700 years. In this section, the project team was not so much concerned with design as with wind hazard—engineers' best estimate of the frequency with which various wind speeds are exceeded. Here is how to calculate a population-weighted-average wind speed for mean recurrence intervals other than 700 years, namely 10, 50, 100, 300, and 1,700 years.

The project team created a spatial overlay that included the remaining mean recurrence interval wind contours and the Atlantic and Gulf Coast state boundaries. This resulted in a set of polygons that represented wind speeds for all mean recurrence intervals for each location. For example, see how various contours for South Florida cross in Figure 4.9, creating polygons with various combinations of wind speeds with 10, 50, 100, 300, 700, and 1,700-year mean recurrence intervals. Rather than deal with the thousands of polygons, the project team estimated the population by 700-year wind speed band and, for each band, calculated the weighted average wind speed for the remaining mean recurrence intervals (10, 50, 100, 300, and 1,700 years) using the population of each polygon.

As a simplified example, suppose the population where 700-year wind speed is approximately 115 mph is 1,000 people. Suppose two contours for the 1,700-year mean recurrence interval intersect the region, one with a population of 750 and a 1,700-year wind speed of 120 mph, and the other with a population of 250 with a 1,700-year wind speed of 130 mph. Thus, 75% of the population have a 1,700-year wind speed of 120 mph and the other 25% have a 1,700-year wind speed of 130 mph, and all 1,000 have a 700-year wind speed of 115 mph. The project team replaced the two subgroups with a single population of 1,000 where 1,700-year wind speed is 0.75·120 mph + 0.25·130 mph = 122.5 mph. That is, treat the hazard where those 1,000 people live as uniform: all 1,000 people are exposed to a 700-year wind speed of 115 mph and a 1,700-year wind speed of 122.5 mph. Table 4-12 shows the resulting weighted average wind speeds by mean recurrence interval. For example, suppose a location has a 700-year wind speed of 110 mph according to the ASCE 7-16 map of basic wind speed for occupancy category II buildings. Reading the first row of Table 4-12, that location would be estimated to have a 10-year wind speed, e.g., the wind speed associated with a mean recurrence interval of 10 years, of 71 mph, as shown in the first column of the first row.

ASCE 7-16 identifies wind-borne debris regions along the Gulf and Atlantic Coast where 700-year wind speeds are greater than 130 mph. The project team created a 1-mile buffer for these areas and intersected with the hazard map through a GIS process. The resulting map allowed the project team to extract the values (mph) for any given return interval, at any location, and identify whether the property is within 1 mile of the coast. Although the 1-mile buffer is not visible at this scale, Figure 4-10 depicts the final hazard map with county boundaries.

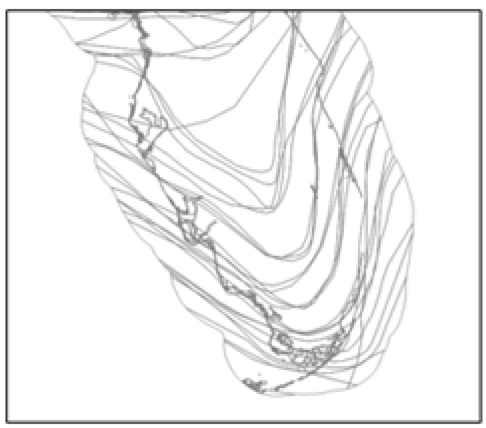


Figure 4-9. South Florida wind speed combination example.

	Mean recurrence interval (years)					
	10	**50**	**100**	**300**	**700(a)**	**1,700**
Population-weighted wind speed (mph)	71	85	95	105	110	120
	71	87	95	105	115	120
	73	91	98	110	120	129
	75	98	107	120	130	139
	77	101	112	129	140	149
	75	100	119	130	145	150
	80	110	121	138	150	161
	80	119	130	149	160	172
	80	120	137	151	170	181
	81	130	147	166	180	196

(a) 700-year wind speed is a baseline, meaning that one applies wind hazard curves—essentially rows in this table—to a location based on its 700-year wind speed. The other columns in the row give the population-weighted average wind speed with the specified mean recurrence interval, even though the wind speed with 10-, 50-, 100-, 300-, or 1,700-year mean recurrence interval may differ at an actual location with the specified 700-year wind speed.

Table 4-12. Population-weighted wind speeds (mph) by return interval, given 700-year wind speed contours.

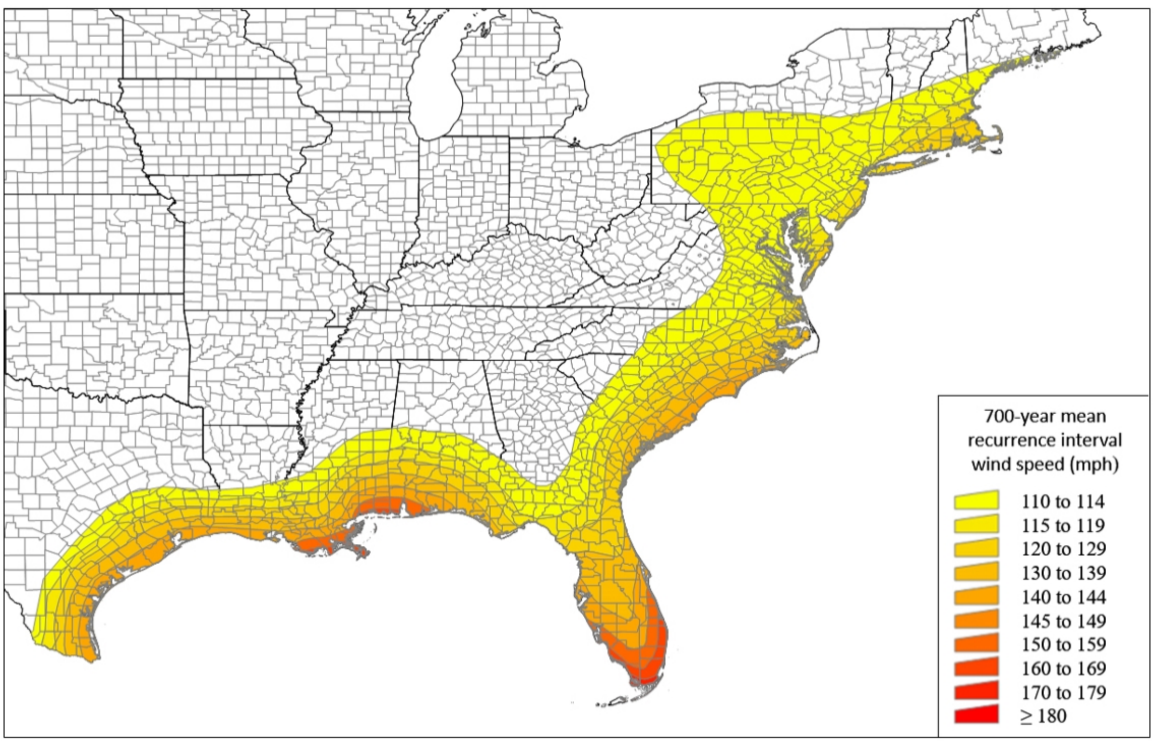


Figure 4-10. ASCE 7-16 700-year wind speeds.

4.10.4 Estimating Tornado Wind Hazard

Because of rapid population growth and observation bias in existing tornado databases, it is difficult to characterize tornado hazard effectively. However, given that tornado shelters mitigate injuries and loss of life only, tornado hazard can be assessed solely based on the number of fatalities, for which there are good statistics. NOAA's NWS (NOAA NWS, 2017) provides a database of fatalities by state and by year from 1950 to 2016. The project team divided these values by the U.S. Census Bureau's (USCB 2017) state population estimates to estimate fatalities per capita per year by state. This analysis assumes safe rooms and shelters are perfectly effective in preventing death and injury when people use them. The analysis excludes data prior to 1950 to recognize the widespread use of tornado sirens and how sirens greatly reduce fatalities.

4.10.5 Estimating Seismic Hazard

This work considers ground shaking as the main peril that causes damage in earthquakes, and ignores other perils such as liquefaction, landsliding, and fault offset. These other perils can be important in certain circumstances. For example, in the 2011 Christchurch, New Zealand earthquake, liquefaction damage contributed a much larger fraction to aggregate loss than is usual in California earthquakes. Closer to home, the 1906 San Francisco earthquake might have had a much milder outcome if liquefaction had not heavily damaged the water supply system. Water supply damage prevented effective fire department response. Fire led to the bulk of the losses and deaths. However, setting aside urban conflagration, shaking tends to dominate U.S. building damage, so focusing on shaking seems reasonable for assessing the costs and benefits of seismic designs to exceed I-Code requirements, and also for assessing federal grants.

The USGS distributes the 2014 National Seismic Hazard Maps (Petersen 2014) in various formats. The most relevant one contains gridded seismic hazard curves for the 48 conterminous states, showing probability in 1 year of shaking exceeding each of 20 levels of spectral acceleration response from less than 0.01 g to more than 5.0 g in logarithmic increments. The hazard curves are calculated for site conditions with average shearwave velocity in the upper 30 meters of soil (Vs30) equal to 760 m/s, corresponding to the boundary between NEHRP site classes B and C.

When the project team commenced the 2017 Interim Study, the 2014 gridded hazard curves were not yet available for Alaska, Hawaii, and other portions of the United States outside the conterminous United States. The USGS has not published the gridded hazard data for any of the 2016 National Seismic Hazard Maps[12], or for the portion of the United States outside the conterminous United States for the 2008 National Seismic Hazard Maps. The project team decided at the beginning of this project not to search for data that were not readily available, even if those data ought to exist. The project team therefore did not contact the USGS in search of either of these unpublished data sets. The project team acquired Vs30 for all U.S. Census tracts using the USGS's OpenSHA site data app, the latest release version as of 29 November 2016, and used the preferred data: generally, Wills and Clahan (2006) for California and Allen and Wald (2007) for other states.

Both groups (Wills at California Geological Survey and Wald at USGS) produced later revisions to their Vs30 maps, but neither had been incorporated into OpenSHA as of the start of this work. The project team opted to use the slightly older maps for convenience and because any errors in the accuracy of Vs30 for individual sites would tend to be cancelled out among the larger sample.

[12] To learn more visit: https://earthquake.usgs.gov/hazards/hazmaps/conterminous/index.php#2016.

Current standard practice requires addressing site amplification using NEHRP site classes rather than Vs30. The project team mapped from Vs30 to NEHRP site class using the same ranges of Vs30 that the 2015 NEHRP Recommended Seismic Provisions (FEMA 2015d) do. The project team did so in two different ways: one using the standard set of NEHRP site classes (A, B, C, D, and E), as in Table 4-13 and another with boundary soil types (e.g., BC, CD, DE), according to Table 4-14. The former is used to calculate design parameters S_{MS} and S_{M1}, while the latter were used to calculate the hazard to which buildings are subjected, with slightly more refinement than the standard NEHRP site amplification allows.

Site class	Vs30 (m/sec)
A	≥ 1500
B	760-1599
C	360-760
D	180-360
E	< 180

Table 4-13. NEHRP site classes and associated Vs30, used for estimating design requirements.

Site class	Vs30 (m/sec)
A	≥ 1780
AB	1260 - 1779
B	900 - 1259
BC	630 - 899
C	430 - 629
CD	300 - 429
D	210 - 299
DE	150 - 209
E	< 150

Table 4-14. NEHRP site classes and boundary classes with Vs30, used for estimating hazard.

To estimate hazard at census-tract centroids, find the nearest four grid points in the gridded national seismic hazard maps, extract their hazard curves from the gridded seismic hazard data, spatially interpolate exceedance frequency at each of many levels of ground motion, and then adjust the interpolated hazard curve to account for its site conditions. The project team made the adjustment by factoring the ground motion on BC soil by the appropriate value of the site coefficient F_a or F_v from table 11.4-2 of FEMA's (2015d) *NEHRP Recommended Provisions*. The project team added F_a and F_v values for the boundary site classes AB, BC, etc., averaging the relevant values, as shown in Table 4-15 and Table 4-16. (Site coefficients increase or decrease spectral acceleration response to account for amplification of ground motion on sites with other values of Vs30 than 760 m/sec.) The result is the ground motion hazard curve to characterize site hazard.

Site class	$h_s = S_a$(0.2 sec, 5%), g[(a)]					
	$h_s \le 0.25$	0.50	0.75	1.00	1.25	$h_s \ge 1.50$
A	0.80	0.80	0.80	0.80	0.80	0.80
AB	0.85	0.85	0.85	0.85	0.85	0.85
B	0.90	0.90	0.90	0.90	0.90	0.90
BC	1.00	1.00	1.00	1.00	1.00	1.00
C	1.30	1.30	1.20	1.20	1.20	1.20
CD	1.45	1.35	1.20	1.15	1.10	1.10
D	1.60	1.40	1.20	1.10	1.00	1.00
DE	2.00	1.55	1.25	1.13	1.00	1.00
E	2.40	1.70	1.30	1.15	1.00	1.00

(a) FEMA (2015) instructs the user to linearly interpolate between values of h_s

Table 4-15. Site coefficient F_a as a function of S_a*(0.2* sec, *5%)* on site class BC, denoted h_s.

Site class	$h_1 = S_a$(1.0 sec, 5%), g[(a)]					
	$h_1 \le 0.10$	0.20	0.30	0.40	0.50	$h_1 \ge 0.60$
A	0.80	0.80	0.80	0.80	0.80	0.80
AB	0.80	0.80	0.80	0.80	0.80	0.80
B	0.80	0.80	0.80	0.80	0.80	0.80
BC	1.00	1.00	1.00	1.00	1.00	1.00
C	1.50	1.50	1.50	1.50	1.50	1.40
CD	1.95	1.86	1.76	1.71	1.66	1.56
D	2.40	2.21	2.01	1.91	1.81	1.71
DE	3.30	2.76	2.41	2.16	2.01	1.86
E	4.20	3.31	2.81	2.41	2.21	2.01

(a) FEMA (2015) instructs the user to linearly interpolate between values of h_1

Table 4-16. Site coefficient F_v as a function of S_a*(1.0* sec, *5%)* on site class BC, denoted h_1.

One can perform the spatial interpolation and site amplification of seismic hazard as follows. Let the longitude λ and latitude α of an arbitrary location within the boundaries of the National Seismic Hazard Mapping Program (NSHMP) be denoted by the coordinate pair (λ,α). Let the NEHRP site class at that location be denoted by σ. Let the hazard curve for an arbitrary location be denoted by an N x 2 array where N rows correspond to the N intensity measure levels of the NSHMP hazard curves. NSHMP presents seismic hazard in terms of N = 20 pairs (h_i, p_i), where h_i denotes the i^{th} intensity measure level and p_i denotes the probability that the site will experience shaking of intensity measure level at least h_i at least once in a given year. One can use Equation 3-16 to convert from 1-year exceedance probability p_i to mean annual exceedance frequency G_i (in units of events per year). Equation 4-16 assumes Poisson arrivals of earthquakes during a 1-year period. The NSHMP provides hazard at 0.05-degree grid points on BC soil. Considering an arbitrary location within the boundaries of the NSHMP map, one finds the four closest grid points. The western and eastern longitudes of the four closest grid points will be denoted by λ_0 and λ_1 respectively, and the southern and northern latitudes of the four nearest grid point by α_0 and α_1 respectively. In order to map to a normalized coordinate system, the coordinates of the southwest, northwest, southeast, and northeast grid points will be denoted by the coordinates (0,0), (0,1), (1,0), and (1,1), respectively. Map the geographic coordinates of the location of interest (λ,α) to a normalized coordinate pair (x^*,y^*) by Equation 4-17, and then interpolate hazard on BC soil at (x^*,y^*) using Equation 4-18.

$$G_i = -ln(1 - p_i)$$
(Equation 4-16)

$$x^* = \frac{\lambda - \lambda_0}{\lambda_1 - \lambda_0}, y^* = \frac{\alpha - \alpha_0}{\alpha_1 - \alpha_0}$$
(Equation 4-17)

$$G_i(x^*, y^*) = a \cdot x^* + b \cdot y^* + c \cdot x^* \cdot y^* + d$$
(Equation 4-18)

Where,

$a = G_i(1{,}0) - G_i(0{,}0)$
$b = G_i(0{,}1) - G_i(0{,}0)$
$c = G_i(1{,}1) + G_i(0{,}0) - G_i(1{,}0) - G_i(0{,}1)$
$d = G_i(0{,}0)$

To account for site amplification or deamplification, use *NEHRP Recommended Provisions* site coefficient F_a or F_v, as appropriate, using Equation 4-19 or 4-20, as is standard accepted practice (FEMA 2015d). Equation 3-19 deals with short-period spectral acceleration response. In the equation, $h_{i,S}$, $F_a(h_{i,S}, \sigma)$, and $h_{i,MS}$ respectively denote 5% damped elastic spectral acceleration response at 0.2-second period at level *i* on BC soil; the short-period amplification factor evaluated at $h_{i,S}$ for site class σ, and the 5% damped spectral acceleration response at 0.2-second period at level *i* on site class σ. Equation 4-20 deals with spectral acceleration response at a 1-second period. In the equation, $h_{i,1}$, $F_v(h_{i,1}, \sigma)$, and $h_{i,M1}$ respectively denote 5% damped elastic spectral acceleration response at 1.0-second period at level *i* on BC soil; the 1-second amplification factor evaluated at $h_{i,1}$ for site class σ, and the 5% damped spectral acceleration response at 1.0-second period at level *i* on site class σ. When estimating hazard at intensity measure levels between any two levels *i* and *i*+1 of the NSHMP, treat the natural logarithm of the exceedance frequency as varying linearly with the intensity measure level, as is common.

$$h_{i,MS} = F_a(h_{i,S}, \sigma) \cdot h_{i,S}$$
(Equation 4-19)

$$h_{i,M1} = F_v(h_{i,1}, \sigma) \cdot h_{i,1}$$
(Equation 4-20)

For example, consider seismic hazard in census tract 06001403100, the one shown in Figure 4-5 with a blue dot, e.g., California (06), Alameda County (001), Tract 403100. The tract's geographic centroid is located at 37.8023N, -122.2755E. OpenSHA's site data application version 1.3.2 shows that on the Wills and Clahan (2006) geologic map of California, the Vs30 at that location is 302 m/sec (Figure 4-11). As shown in Table 4-14, 302 m/sec corresponds to site class CD.

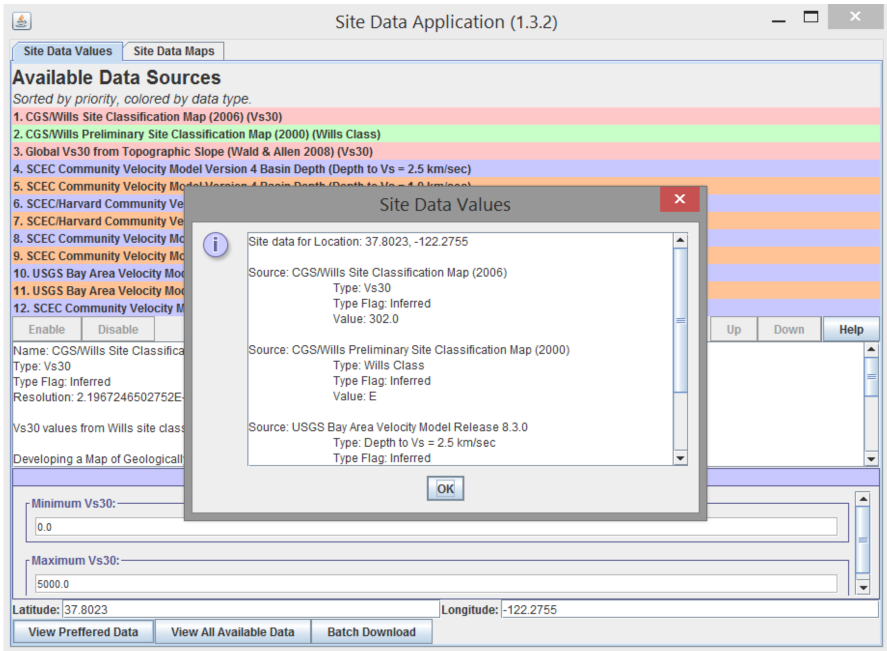


Figure 4-11. Sample calculation of Vs30 using OpenSHA site data application.

According to the NSHMP, the hazard in terms of 1-sec 5%-damped spectral acceleration response at four nearby locations (37.80N, -122.30E), (37.85N, -122.30E), (37.80N, -122.25E), and (38.85N, -122.25E) on a hypothetical site (*x*,*y*) with Vs30 = 760 m/sec is as shown in Figure 4-12A. (This example deals with the constant-velocity portion of the response spectrum, but it is only an example. Similar procedures apply to the constant-acceleration portion of the response spectrum.) The coordinates of the site in question (37.8023N, -122.2755E) can be mapped to the normalized coordinates (*x**,*y**) by Equation 4-17 as follows:

$$x^* = \frac{\lambda - \lambda_0}{\lambda_1 - \lambda_0} = \frac{-122.2755 + 122.30}{-122.25 + 122.30} = 0.49$$
$$y^* = \frac{\alpha - \alpha_0}{\alpha_1 - \alpha_0} = \frac{37.8023 - 37.80}{37.85 - 37.80} = 0.045$$

NSHMP estimates the 1-year exceedance probability *p* of S_a(1.0 sec, 5%) = 0.0025g on site class BC as shown in the column labeled *p* in Table 4-17. Calculate exceedance frequency for each grid point using Equation 4-16, e.g., for the first row,

$$G_i = -ln(1 - p_i) = -ln(1 - 0.54841) = 0.7950$$

Lat N	Lon E	Coords	*P*	*G*, yr^{-1}
37.80	-122.30	(0,0)	0.54841	0.7950
37.85	-122.30	(0,1)	0.54614	0.7900
37.80	-122.25	(1,0)	0.55668	0.8135
37.85	-122.25	(1,1)	0.55337	0.8060

Table 4-17. Sample calculation of G for S_a(1.0 sec, 5%, BC) = 0.0025g.

Then calculate the exceedance frequency of S_a(1.0 sec, 5%, BC) = 0.0025g at (x*, y*) using Equation 4-18:

$$a = G_i(1,0) - G_i(0,0) = 0.8135 - 0.7950 = 0.0185$$
$$b = G_i(0,1) - G_i(0,0) = 0.7900 - 0.7950 = -0.0050$$
$$c = G_i(1,1) + G_i(0,0) - G_i(1,0) - G_i(0,1) = 0.8060 + 0.7950 - 0.8135 - 0.7900 = -0.0025$$
$$d = G_i(0,0) = 0.7950$$

(Equation 4-18)

$$G_i(x^*, y^*) = a \cdot x^* + b \cdot y^* + c \cdot x^* \cdot y^* + d = 0.0185 \cdot 0.49 - 0.0050 \cdot 0.045 - 0.0025 \cdot 0.49 \cdot 0.045 + 0.7950 = 0.8037$$

(Equation 4-19)

Repeating for all other values of h_1 produces the hazard curve shown in Figure 4-12A for a site at location (x*,y*) and site class BC.

Now consider site hazard accounting for site amplification. The site class of the site of interest is CD. Recall that here, h_1 = 0.0025g (the first value in each hazard curve of the NSHMP gridded seismic hazard data for 1-second spectral acceleration response). Referring to Table 4-16, the row labeled “CD” and the column labeled $h_1 \leq 0.10$g, F_v = 1.95. Thus, by Equation 4-20,

$$h_{M1} = F_v(h_1, \sigma) \cdot h_1 = 1.95 \cdot 0.0025g \ = \ 0.0049g$$

(Equation 4-20)

Repeating for all other values of h_{M1}, after adjusting for site amplification on a site with Vs30 = 302 m/sec, site (x*, y*) on site class CD has a hazard curve shown in Figure 4-12B.

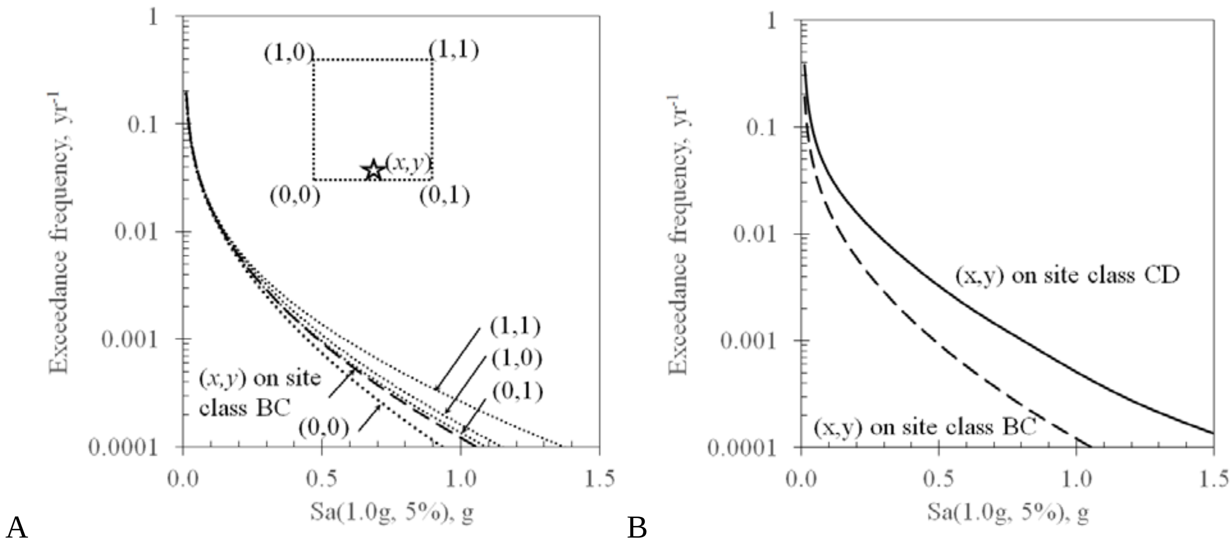


Figure 4-12. (A) Spatial interpolation of site hazard followed by (B) factoring for site effects.

The project team stratified hazard using FEMA P-154 (2015e) seismicity regions, as defined in that document's Table 2-2 (duplicated in Table 4-18), and mapped in its Figure A-1 (duplicated in Figure 4-13). The map assigns to a county the highest hazard anywhere in that county. However, the figure is *only* used to stratify the sample, not to quantify site-specific hazard for calculating BCR. The actual site-specific hazard is used in the calculation of each mitigation effort's BCR.

Seismicity Region		Spectral Acceleration Response, S_S (short-period, or 0.2 seconds)	Spectral Acceleration Response, S_1 (long-period, or 1.0 second)
	Low	less than 0.250g	less than 0.100g
	Moderate	greater than or equal to 0.250g but less than 0.500g	greater than or equal to 0.100g but less than 0.200g
	Moderately High	greater than or equal to 0.500g but less than 1.000g	greater than or equal to 0.200g but less than 0.400g
	High	greater than or equal to 1.000g but less than 1.500g	greater than or equal to 0.400g but less than 0.600g
	Very High	greater than or equal to 1.500g	greater than or equal to 0.600g

Notes: g = acceleration of gravity in horizontal direction

Table 4-18. Definition of FEMA P-154 (2015e) seismicity regions.

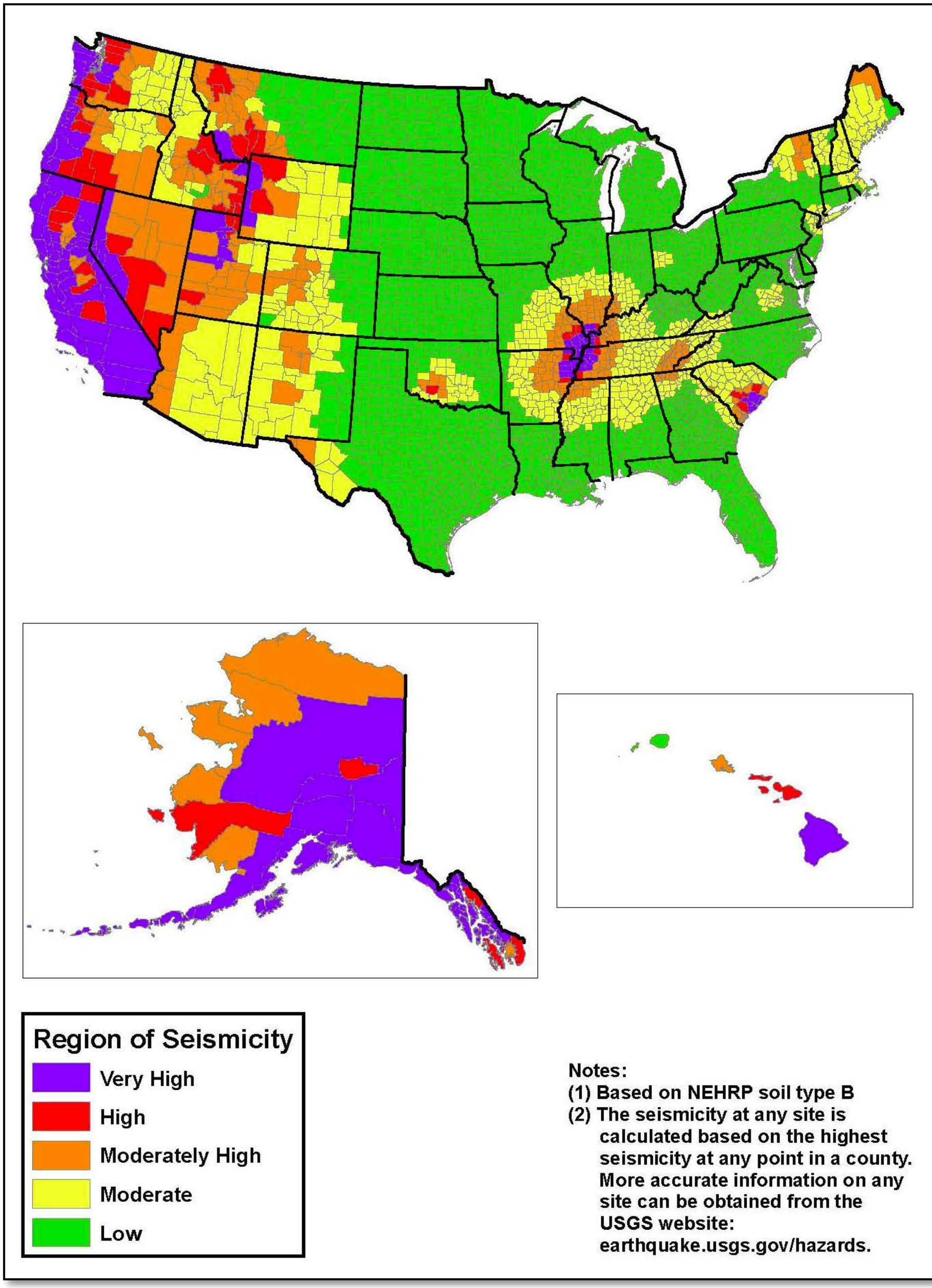


Figure 4-13. FEMA P-154 (2015e) seismicity regions.

4.10.6 Estimating Fire Hazard

Similar to earthquake, flood, and other hazards, fires at the WUI (WUI fires) have been the subject of considerable analysis and mapping by federal agencies, particularly the U.S. Forest Service (USFS), who used simulation to develop a national map of BPs (Finney et al. 2011; Short et al. 2016). Burn probability here means the number of times a location experiences wildland fire (either by initiation or extension) per year. This WUI fire hazard mapping appears to be the most detailed and extensive of its kind, unique at the national level. This Interim Study employs it, as do many insurers. BP estimates the occurrence probability of a fire, but does not indicate the intensity of the fire, which is a function of fuel and other factors. Fire intensity level (FIL), also termed fireline intensity (FLI), measures the rate of heat release per unit length of flaming fire front (kW/m), regardless of flame front depth (Byram 1959; Scott 2013). Similar to BPs, an FIL dataset is available for the conterminous United States (Short et al. 2016). The product of BP and FIL provides a probability of FIL and ignition.

The project team assigned high, medium, and low WUI fire hazard strata based on USFS Wildfire Hazard Potential (WHP). Figure 4-14 presents maps of the conterminous United States for both BPs and WHPs. The project team mapped USFS WHP to hazard categories low, medium, and high hazard for sampling purposes as shown in Table 4-19. Under this stratification scheme, an approximately equal number of counties in the conterminous United States can be considered low, medium, and high hazard, as shown in Figure 4-15. The project team used the strata for purposes of stratified sampling of wildfire-related grants from HMGP, PA, etc.

USFS WHP	Number of counties	Area of counties	MSv2 fire hazard
1	6%	1%	Low
2	9%	3%	Low
3	15%	9%	Low
4	33%	24%	Moderate
5	37%	63%	High

Table 4-19. Mapping 2014 USFS WHP to the 2017 *Mitigation Saves* fire hazard strata for purposes of sample stratification.

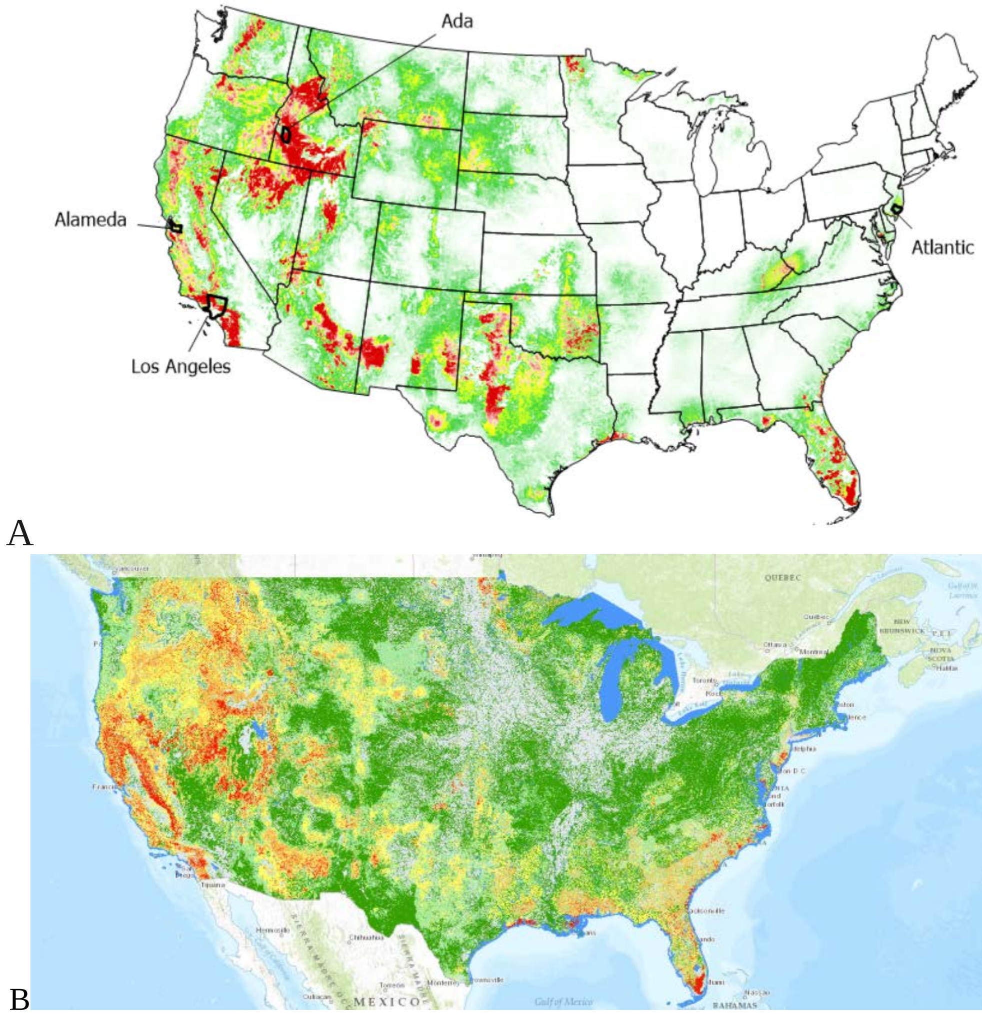


Figure 4-14. (A) USFS BPs with four study counties indicated. (B) USFS 2014 wildfire hazard potential, plus water and non-burnable areas.

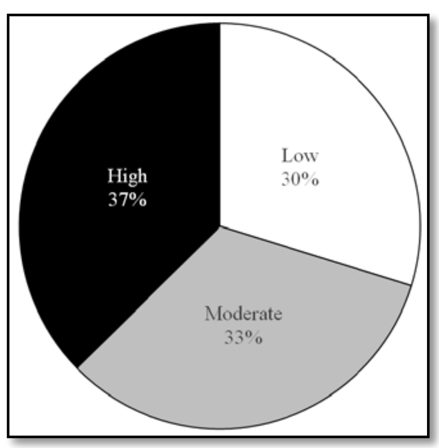


Figure 4-15. Number of U.S. counties in the conterminous United States by 2017 *Mitigation Saves* fire hazard stratum.

Equation 4-21 provides the calculation of EAL using the terminology of fire-protection engineers:

$$EAL = \sum_{i=all\ CBs} V_{i,k} BP_i \ FP_i SE_{BP_i} \sum_{FIL=1,6} FIL_{i,j} RF_{j,k}$$

(Equation 4-21)

Where,

EAL = expected annualized loss
$V_{i,k}$ = value in grid cell i of exposure type k (only k=1 is used here)
BP_i = one-year burn probability in grid cell i
FP_i = fire penetration of WUI fire into the census block corresponding to grid cell i
SE_{BPi} = suppression effectiveness, a function of burn probability in grid cell i
$FIL_{i,j}$ = jth class of fireline intensity in grid cell i
$RF_{j,k}$ = response function for exposure type k given FIL_j

FP_i,, the fire penetration of wildland-urban-interface fire into the census block corresponding to grid cell i, is taken as 700m based on Chen and McAneney (2004). Specifically, the project team approximated each census block as a square, and the fraction of the square's area equal to length of a side multiplied by 700m was taken as FP_i.

SE_{BPi},, the suppression effectiveness (a function of burn probability in grid cell i) accounts for active fire suppression. It is well known that two types of fire occur at the WUI: (1) fires that are small enough for fire departments or possibly homeowners to suppress and thereby protect buildings, and (2) fires that are so large that they overwhelm fire responders, and make it less likely that fire responders can protect buildings. Ideally, suppression effectiveness, *SE*, should be a function of fire size and available fire resources. It is modeled that way for fire following earthquake (TCLEE 2005). It could be done that way in principle for fires at the WUI. It was impractical for United States to process a stochastic set of fires on a national scale within the constraints of the present project. Instead, the project team took burn probability (*BP*) as a proxy measure of *SE*. The size of fires at the WUI approximately follows a power law (Finney et al. 2011), the exponent of which for California was found to be -1.38. The project team used that value to develop the function SE_{BPi}.

4.11 Estimating Vulnerability

4.11.1 Estimating Vulnerability in General

In this part of the Interim Study, the project team used vulnerability in the engineering sense, which means the relationship between a scalar measure of environmental excitation (e.g., momentum flux in the case of flooding in a velocity zone such as a stream or seashore) and a scalar degree of loss (e.g., repair cost as a fraction of replacement cost, new). A vulnerability function refers here to a curve in *x*-*y* space where *x* measures environmental excitation, *y* measures the expected value of loss, and the curve represents the performance of a specified asset class, such as a woodframe single-family dwelling built after 2012. Elsewhere, the Interim Study uses the term vulnerability in its social-science context.

The project team does not use the words vulnerability and fragility interchangeably. As used here, fragility refers to the relationship between environmental excitation and the occurrence probability of some undesirable outcome, such as the collapse of a building. A fragility function refers here to a curve in *x*-*y* space where *x* measures environmental excitation, *y* measures the occurrence probability of some undesirable outcome, and the curve represents the performance of a specified asset class.

Terminology varies between perils. Some people use the phrases response function, damage function, vulnerability curve, damage curve, and possibly other terms to mean the same thing meant here by vulnerability function. Faced with a choice between using a consistent term across all perils and using numerous terms that may be more familiar to experts within each discipline (fire, flood, wind, etc.), the project team opted for the former choice for consistency.

Some mitigation measures examined here have been well studied and their vulnerability functions developed elsewhere. For example, riverine flood vulnerability (more commonly referred to as depth-damage relationships) is explained in detail in documentation of the Hazus flood module's technical manual (FEMA 2011b). Where it is practical to do so, the present Interim Study relies on existing vulnerability relationships and simply refers the interested reader to the relevant documentation, without repeating it here.

In other cases, especially to examine IBHS FORTIFIED Home Hurricane mitigation measures and adoption of the 2015 IWUIC, the project team used existing vulnerability functions as-is or with slight modification, but only after performing some mapping from the features of the mitigation measures to those existing vulnerability functions. In still others, especially designing to exceed I-Code requirements for earthquake loads, neither Hazus nor other resources offer existing vulnerability functions. Transparency requires providing a lot of detail for those cases. As a result of the differences between perils in the availability of vulnerability functions, some of the following sections are short and provide little detail, while some are long.

4.11.2 Estimating Riverine Flood Vulnerability

The project team used the flood vulnerability functions already encoded in Hazus to assess the relationship between flood depth and losses. For details, see the Hazus flood technical manual (FEMA 2011b).

4.11.3 Estimating Coastal Flooding Vulnerability

The project team estimated coastal flood vulnerability here using the FEMA BCA re-engineering (BCAR) vulnerability functions that are available within Hazus. The environmental excitation that the vulnerability functions take as input is flooding depth. The vulnerability function estimates repair costs as output. The flooding depth of a building is taken as the height of stillwater depth with wave height minus the elevation of the first floor, denoted here by H, which is taken as various heights above BFE. See Equation 4-22. Recall that BFE is calculated using Equation 4-14. The project team did not analyze the cost-effectiveness of building above coastal A-zones because these zones are not identified in the NFIP data.

$$D = (NOAA\ MOMs\ surge\ height + sea\ level\ rise) * 1.55 - H$$
(Equation 4-22)

The suite of available vulnerability functions differs significantly by wave height because the damage capacity of a wave varies significantly with its size. The estimated height above the BFE is added to the additional height of the structure to determine the vulnerability function used in the equation. The foundation of a coastal home is assumed to be open in all analyses here.

4.11.4 Estimating Hurricane Wind Vulnerability

Hurricane wind vulnerability is estimated using the damage functions readily available within Hazus. The project team is interested in the cost-effectiveness of constructing new buildings to satisfy the requirements of the IBHS FORTIFIED Home Hurricane program, which specifies particular design requirements that in many cases exceed those of the 2015 I-Codes, so one needs to characterize the vulnerability of buildings that satisfy the requirements of IBHS FORTIFIED Home. The project team mapped the required building options for each FORTIFIED Home designation to the corresponding Hazus damage function parameter, adjusting where necessary. This section describes this process in detail. See Table 4-20 through Table 4-23 for a summary. Certain mitigation measures could not be modeled with existing Hazus damage functions, so were adjusted either using expert judgment or modified from hurricane mitigation studies.

To calculate the performance improvement associated with each IBHS FORTIFIED Home Hurricane program level (Bronze, Silver or Gold designation), the project team constructed a base-case vulnerability function. The base case reflects a 2,000 sf, single-story, wood-framed single-family dwelling that complies with the 2015 IRC and adheres to all provisions required for hurricane wind resistance. The house has a hip roof and costs $105 per square foot to build (e.g., not including land). The cost is based on construction estimates provided by the National Association of Home Builders (NAHB 2015).
Note that in some locations, state and local requirements exceed those of the IRC, such as those adopted after Hurricane Andrew in Miami-Dade or Broward Counties. The project team did not consider these local differences from the IRC, and did not calculate the BCR of exceeding them.

The base case typically remains constant throughout most of the wind speed bands described in Section 4.10.3. Two exceptions: (1) locations where the 700-year wind speed lies between 130-140 mph and the site is within 1 mile of the coastline, and (2) locations where 700-year wind speed exceeds 140 mph. The project team also updated the base case in areas where wind-borne debris would be expected. For regions with 700-year wind speed less than 130 mph, the base-case vulnerability function assumes the following details: roof nailing uses 8d nails at 6"/12"[13], no secondary water resistance, toe-nail roof-to-wall connections, and openings are not protected. For those homes in regions where 700-year wind speeds exceed 130 mph, the base case assumes the following: roof nailing uses 8d nails at 4"/4", no secondary water resistance, a continuous load path is developed via installation of hurricane straps for roof to wall connections, and openings are protected (where required).

The FORTIFIED Home High-Wind program is applicable for regions where design wind speeds are expected to be less than 115 mph. Because a FORTIFIED Silver dwelling assumes upgrades

[13] This identifies the nail spacing requirements around the edges and within the interior field.

to gable end bracing and porch connections, this option was not appropriate (e.g., the base case assumes hip roofs and no porch present). Bronze-level upgrades protect the roof system by tightening the roof nailing schedule from 8d at 6"/12" to 8d at 6"/6" and replacing smooth shank nails with ring-shank nails. Secondary water resistance is addressed with both the installation of contouring seam tape and wind-driven water-resistant attic vents. Gold-level upgrades involve reinforcing garages with increased panel bracing plus more rollers with steel axels and wheels, and more brackets for tracks. A continuous load path is developed with the addition of hurricane straps in lieu of roof-wall toe-nail connection. See Table 4-20 for details and costs.

		Improvement category	IBHS FORTIFIED	Hazus equivalent	IRC	Hazus equivalent	Estimated cost increase for 2,000 sf house
IBHS FORTIFIED Home Designation	Bronze	Roof deck attachment	8d ring-shank @ 6"/6"	8d @ 6"/6"	8d smooth-shank @ 6"/12"	8d @ 6"/12"	$100
IBHS FORTIFIED Home Designation	Bronze	Secondary water resistance	Yes; roof deck and attic ventilation	Yes	No	No	$800
IBHS FORTIFIED Home Designation	Silver	Opening Protection	Not required				
IBHS FORTIFIED Home Designation	Silver	Gable end bracing	Strap & block rat-runs	N/A	N/A	N/A	$500 each
IBHS FORTIFIED Home Designation	Silver	Porch connections	Enhance resistance to uplift	N/A	N/A	N/A	$500 each
IBHS FORTIFIED Home Designation	Gold	Garage door upgrade	Pressure rated for 140 mph Exposure Category B	Standard	115 mph pressure rated	Weak	$500 each
IBHS FORTIFIED Home Designation	Gold	Continuous load path upgrade	Prescriptive requirements avoid specific engineering	Hurricane strap	IRC prescriptive requirements	Toe-nail	1.5% of construction costs

Table 4-20. Hazus modeling of IBHS FORTIFIED Home Hurricane and 2015 IRC for basic wind speed < 115 mph.

For regions with design wind speeds between 115 and 130 mph, the FORTIFIED Home Hurricane program is available. Bronze upgrades are essentially the same as those described above for basic wind speeds less than 115 mph. Silver upgrades protect openings with installation of wood structural panels. Gold upgrades are the same as those described for wind speeds less than 115 mph. A continuous load path is developed with the addition of hurricane straps in lieu of roof-wall toe-nail connection. See Table 4-21 for details and costs.

IBHS FORTIFIED Home Designation		Improvement category	IBHS FORTIFIED	Hazus equivalent	IRC	Hazus equivalent	Estimated cost increase for 2,000 sf house
	Bronze	Roof deck attachment	8d ring-shank @ 6"/6"	8d @ 6"/6"	8d smooth-shank @ 6"/12"	8d @ 6"/12"	$175
	Bronze	Secondary water resistance	Yes; roof deck and attic ventilation	Yes	No	No	$800
	Silver	Opening Protection	Wood Structural panels	Weak	None	None	$3,000
	Silver	Gable end bracing	Strap & block rat-runs	N/A	N/A	N/A	$500 each
	Silver	Porch connections	Enhance resistance to uplift	N/A	Usually not well anchored against uplift	N/A	$500 each
	Gold	Garage door upgrade	Pressure rated for local design wind speed	Standard	Probably not rated	Weak	$500 each
	Gold	Continuous load path upgrade	Prescriptive requirements or engineering design	Hurricane strap	Toe-nailed unless load over 200 lbs	Toe-nail	1.5% of construction costs

Table 4-21. Hazus modeling of IBHS FORTIFIED Home Hurricane and 2015 IRC for basic wind speeds of 115-130 mph.

For regions with basic wind speeds greater than 130 mph and less than 140 mph and more than 1 mile from the coast, the FORTIFIED Home Hurricane program is available. Bronze upgrades add secondary water resistance with both the installation of contouring seam tape and wind-driven water-resistant attic vents. Silver upgrades protect openings with installation of wood structural panels. Gold upgrades are not available since all prescriptive requirements are already required by code. See Table 4-22 for details and costs.

IBHS FORTIFIED Home Designation	Improvement category	IBHS FORTIFIED	Hazus equivalent	IRC	Hazus equivalent	Estimated cost increase for 2,000 sf house
Bronze	Roof deck attachment	8d ring-shank @ 6"/6"	8d @ 6"/6"	8d smooth-shank @ 4"/4"	8d @ 6"/6"	None
Bronze	Secondary water resistance	Yes; roof deck and attic ventilation	Yes	No	No	$800
Silver	Opening protection	Wood structural panels	Weak	None	None	$3,000
Silver	Gable end bracing	Strap & block rat-runs	N/A	Strap & block rat-runs	N/A	None
Silver	Porch connections	Designed for local design wind speed	N/A	Designed for local design wind speed	N/A	None
Gold	Garage door upgrade	Rated for local design wind speed	Standard	Rated for local design wind speed	Standard	None
Gold	Continuous load path upgrade	Prescriptive requirements avoid specific engineering	Hurricane strap	IRC prescriptive requirements	Hurricane strap	None

Table 4-22. Hazus modeling of IBHS FORTIFIED Home Hurricane and 2015 IRC for basic wind speeds of 130-140 mph and more than 1 mile from coast.

For regions with design wind speeds greater than 130 mph and less than 1 mile from the coast or wind speeds are greater than 140 mph, the FORTIFIED Home Hurricane program is available. Bronze upgrades are essentially the same as those described above for wind speeds between 130 mph and 140 mph. Silver upgrades improve the opening protection by requiring ASTM/IRC approved impact-rated products. Gold upgrades are not available since all prescriptive requirements are already required by code. See Table 4-23 for details and costs.

The project team estimated costs for the improvements using RSMeans construction cost data and modified them with advice from industry professionals familiar with implemented costs of the IBHS FORTIFIED program. Improvements at the various FORTIFIED levels reflect the additional costs to build above current IRC requirements. Costs are considered modest for such improvements, e.g., replacing smooth shank nails with ring shank nails for roof sheathing attachments costs approximately $100. Taping seams for secondary water resistance costs approximately $800.

IBHS FORTIFIED Home Designation	Improvement category	IBHS FORTIFIED	Hazus equivalent	IRC	Hazus equivalent	Estimated cost increase for 2,000 sf house
Bronze	Roof deck attachment	8d ring-shank @ 6"/6" or tighter spacing	8d @ 6"/6"	8d or larger smooth-shank @ 4"/4"	8d @ 6"/6"	None
Bronze	Secondary water resistance	Yes; roof deck and attic ventilation	Yes	No	No	$800
Silver	Opening protection	ASTM/IRC approved impact-rated product	Standard	Code minimum is wood structural panels	Weak	$4,000
Silver	Gable end bracing	Strap & block rat-runs	N/A	Strap & block rat runs	N/A	None
Silver	Porch connections	Designed for local design wind speed	N/A	Designed for local design wind speed	N/A	None
Gold	Garage door upgrade	Rated for local design wind speed	Standard	Rated for local design wind speed	Standard	None
Gold	Continuous load path upgrade	Prescriptive requirements avoid specific engineering	Hurricane strap	IRC prescriptive requirements	Hurricane strap	None

Table 4-23. Hazus modeling of IBHS FORTIFIED Home Hurricane and 2015 IRC for basic wind speed at least 130 mph and less than 1 mile from coast, or based wind speed at least 140 mph regardless of coastal distance.

Some vulnerability effects of IBHS FORTIFIED Home Hurricane requirements cannot be modeled with the existing Hazus, such as replacing smooth-shank with ring-shank nails for the roof diaphragm nailing. The project team estimated, with input from industry professionals, a 5% reduction in repair cost, based on the increased uplift resistance of the roof diaphragm. Nor can Hazus model installation of wood structural panels for opening protection, as in the FORTIFIED Silver program. A modified damage function was generated using an Applied Research Associates, Inc.'s *2008 Florida Residential Wind Loss Mitigation Study* (ARA 2008), which provides relative loss values from no shutter to basic, plywood or oriented strand board (OSB) shutters. Protecting openings with wood structural panels reduces repair costs by approximately 22% relative to the base case.

4.11.5 Estimating Seismic Vulnerability

The project team considered several options for estimating seismic vulnerability. (See Table 4-24.) In light of the advantages and disadvantages, the project team opted to use the modified Hazus vulnerability approach for repair cost, casualties, and downtime. The Hazus vulnerability approach addresses both structural and nonstructural vulnerability, and recognizes that increased stiffness can aggravate damage to acceleration-sensitive nonstructural components. Note that in many locations, particularly in the central and eastern United States, wind design may govern the lateral strength of many buildings. Increases in seismic design requirements may not increase the design strength or the construction cost of the building, nor produce the benefits one estimates based on seismic design requirements alone. In these cases, the costs and benefits would not apply. The project team did not attempt to identify locations where wind design governs or remove the costs and benefits from the overall calculation. Since the states with the highest seismic risk, and therefore where seismic-responsive design is required, contribute the vast majority of the costs and benefits of seismic design to exceed I-Code requirements, the project team felt the benefits and costs in this situation would be minimal.

For an overview of the project's approach for repair costs, casualties, and duration of loss of function, see Porter (2009a, b). For evidence about the cost to exceed 2015 I-Code requirements see Porter (2016a), which examines the cost from several different perspectives. See Appendix K of this Interim Study for the fine details of how the project team applied those three works to the problem of calculating the vulnerability of code-level and above-code buildings designed for site-specific seismic hazard, and how the project team applied those vulnerability functions to an estimated inventory of present-day buildings across the 48 contiguous United States.

The project team considered various levels of detail for presenting BCR, including: by census block, tract, county, state, or national level; or by model building type and occupancy, model building type alone, occupancy alone, or at some aggregate level. It seemed practical and desirable to provide geographic detail, but providing detail both by geographic area and by some subgroup of buildings (either model building type, occupancy category, or both) would overwhelm readers. The project team opted to provide BCRs for the aggregate building stock of ordinary buildings (risk category II) at the county level, which readers could readily discern in printed maps. As a result, the averages produced here may overestimate BCR for some occupancies and building types, and underestimate them for others.

The project team acknowledged the limitations of the selected approach, but it is practical and consistent with FEMA's own preferred tools for BCA of earthquake risk mitigation: Hazus and the FEMA BCA Tool. The combination of FEMA P-58 and GEM is impractical for present purposes.

Option	Advantages	Disadvantages
Hazus high code (for risk category II) and special high code (risk category IV) (Porter 2009a, 2009b)	Well documented, fairly authoritative, nearly exhaustive	Inconsistent with ASCE 7-10 collapse fragility model. San Francisco CAPSS project (Porter 2012) shows highly uncertain assumptions are required to map Hazus damage states to ATC-20-1 (2005) tag color. Hazus stiffness for special high code is equal to high code, whereas greater strength is probably accompanied by greater stiffness. Does not reflect site-specific seismic hazard.
Modified Hazus: apply Hazus math but with Cs based on design for site-specific hazard and R based on model building types of recent vintage. Tabulate per Porter (2009a, 2009b)	Leverages advantages of Hazus approach while better reflecting loss reduction resulting from greater strength and stiffness. Reflects site-specific hazard. Practical at national scale.	Capacity spectrum method is old technology and can yield inaccurate results for the performance point, especially for low-rise construction.
Commercial catastrophe risk models, e.g., RMS, AIR, Core Logic	Accepted by insurance industry, substantial empirical basis for building categories that were present and insured in large numbers in California in 1989 and 1994.	Proprietary; not peer reviewed; scant or no empirical basis for functions for U.S. buildings other than California construction present and insured in large numbers in 1989 and 1994; based on insured buildings and therefore possibly biased. No basis for designing to exceed I-Code requirements. Might not reflect site-specific seismic hazard.
ASCE-7-based collapse, red-tag, and yellow-tag fragility functions (Porter 2016)	Uses collapse fragility model underlying ASCE 7-10; strong empirical basis for red- and yellow-tagging as multiples of collapses. Treats site-specific seismic hazard.	No model of repair cost, casualties, or repair duration.
PBEE-2 (FEMA P-58; Applied Technology Council 2012)	State of the art for single buildings.	Does not treat building classes. Impractical at national scale. See Box 4-2 for more discussion.
Global Earthquake Model (GEM) analytical approach (Porter et al. 2015), using SP3 for efficiency	General applicability for repair cost	Time consuming; requires survey of relevant attributes in many geographic regions; requires constructing (at least simplified) FEMA P-58 models of 1, 3, or 7 samples of every building type in each geographic region. Never exercised for downtime or casualties. See Box 4-2.

Table 4-24. Selection of method to estimate seismic vulnerability.

Despite the references to Porter (2009a, b, and 2016a), the project team also provided a brief summary of the Hazus vulnerability methodology. A building is idealized as a single-degree-of-freedom nonlinear harmonic oscillator with an elastic-softening-perfectly-plastic pushover curve. The capacity-spectrum method of structural analysis is used to estimate the acceleration and displacement of the building, as illustrated in Figure 4-16. In the figure, the capacity curve represents the relationship between displacement and acceleration of the building over a range of ground motions. The input spectrum idealizes the excitation that an earthquake of a given magnitude, distance, and region imposes on undamaged buildings. The demand spectrum idealizes the excitation that the earthquake imposes on damaged buildings. The performance point represents an estimate of the displacement and acceleration that the earthquake imposes on the particular building with the given capacity curve.

The estimated structural response (the acceleration and displacement of the oscillator at eth performance point) is input to a set of fragility functions that produce an estimate of probabilistic damage to three generalized building components: structural, non-structural drift-sensitive, and non-structural acceleration-sensitive components. Then estimate loss, in each of several measures, especially (1) repair costs as a function of the damage, (2) fatal and nonfatal injuries, and (3) loss-of-use duration. The estimate of repair costs depends on the probabilistic damage state of the three components and the cost to repair the damage from each possible damage state for each component. Repair costs also depend on the building occupancy, because the relative value of the three components varies between occupancy classes. The estimates of injuries and restoration time depend only on the structural damage. Appendix K provides details of the methodology.

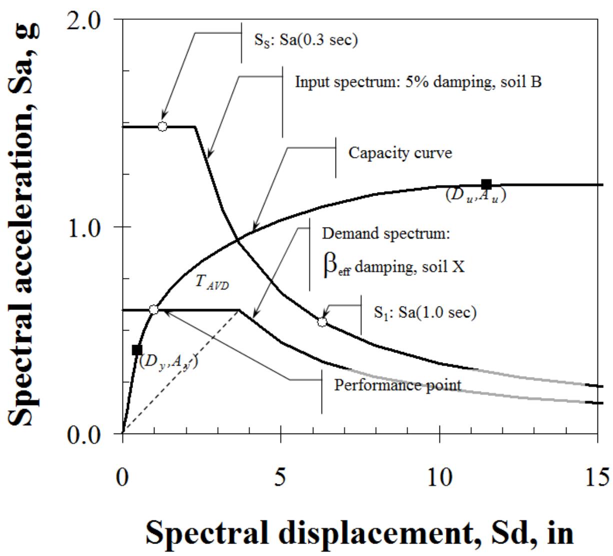


Figure 4-16. Capacity spectrum method of structural analysis.

Box 4-2. Using Hazus Rather Than FEMA P-58 and GEM to Assess the Cost-Effectiveness of Designing to Exceed I-Code Requirements for Earthquake

Some structural engineers strongly endorse FEMA P-58 (FEMA, 2012d) and criticize the capacity-spectrum method of structural analysis employed by Hazus. In the project team's opinion, FEMA P-58 produces more-credible vulnerability functions for individual buildings than does a Hazus-based approach. Project team members helped to lead development of FEMA P-58 and its underlying theoretical basis and initial case studies (e.g., Porter, 2000, Porter, 2003, Krawinkler et al., 2005). However, FEMA P-58 is building-specific. It does not produce vulnerability functions that apply to a building class.

One can use the GEM analytical methodology (Porter et al., 2014) to design probabilistically representative specimens of a building class and analyze them with FEMA P-58 to construct vulnerability functions for a building class. The resulting vulnerability functions are probably more credible than those produced by a Hazus-based approach.

However, practicality forbids the use of the GEM methodology as well. To create a single defensible FEMA P-58 vulnerability function can take hours, days, or more, depending on how much simplification one accepts in the structural modeling. To create a vulnerability function for a building type using the GEM analytical methodology requires between 1 and 7 vulnerability functions created using FEMA P-58. The proper selection of the engineering attributes of those 1 to 7 buildings (number of stories, degree of vertical irregularity, etc.) requires observation and statistical combination of hundreds of real buildings. Nobody has compiled those statistics for the U.S. building stock. Project team members have found by actual practice that compiling those statistics takes tens or hundreds of labor-hours per building type.

Depending on how much detail one wants, the inventory of U.S. buildings includes at least dozens of combinations of building type and height category. Hazus for example categorizes the building stock in 1,008 combinations of model building type, height category, and occupancy class, each of which would require statistics on height and irregularities, and each of which would require 1 to 7 FEMA P-58 models. Each such combination must be designed and analyzed for each of many levels of MCE_R motion and each of many levels of strength and stiffness (I_e)—on the order of 5 to 10 of each, meaning that a GEM approach, using FEMA P-58, would require design and analysis of between 100,000 and 700,000 buildings.

Thus, to create reasonably defensible vulnerability functions for perhaps 700,000 combinations of model building type, height category, occupancy class, S_S or S_1 level, and I_e, would take millions of labor hours, at least as the task is conceived here. No superior, less time-consuming approach appears to exist. By contrast, the Hazus-based approach can be entirely automated using existing math and parameter values. Furthermore, a Hazus-based approach is consistent with FEMA BCA. The Hazus approach has its disadvantages, such as its reliance on the capacity spectrum method (see Table 4-24), but it seems to be a practical, albeit imperfect, solution. FEMA P-58 and GEM by contrast may be excellent solutions, but are impractical for this problem.

4.11.6 Estimating Fire Vulnerability

Understanding the vulnerability of buildings to fire has been the subject of much work. Researchers generally treat building ignition from external fires as resulting from one or more of several phenomena: heat radiation, convection, or conduction (the last cause being less significant). Real buildings ignite by heat build-up, which causes a temperature rise of exposed cladding, roofing, and contents. Buildings also ignite because flames impinge on the building and because of convection of hot gases from the external fire. Firebrands also cause ignitions: burning pieces of wood, carried aloft by hot gases, land on and ignite the roof, debris-filled gutters, or other parts of the building. Many researchers have studied firebrands in WUI fires (e.g., Koo et al., 2010; Manzello et al., 2005, 2006a, 2006b; Pagni and Woycheese, 2000), but still have difficulty quantifying their effects (Mell et al., 2009).

One can employ principles of heat transfer and fire-protection engineering to assess how quickly and in what way a particular, well-specified building or its furnishings is likely to ignite under fire attack, and how quickly fire will spread (Cohen, 1995; Drysdale, 1999; Himoto and Tanaka, 2008; Quintiere, 1998). These approaches are difficult to impractical to apply to the present project, which deals with large numbers of buildings with widely varying designs and without building-specific information (Lee et al., 2008).

The other alternative to estimate inter-building fire spread at the urban or WUI scale is to use empirical or expert-opinion models (Gollner et al. 2015; Hakes et al. 2017). The project team uses that approach for practical reasons.

The project team estimated two cases of the fire vulnerability of a prototype building: 1) not compliant with the 2015 IWUIC and 2) compliant. Both represent a single-family wood-framed dwelling. The non-compliant building is assumed to be wood framed with combustible (e.g., wood) cladding and roofing; no automatic sprinklers; no underfloor enclosure; non-fire rated single-pane glazing and doors; unprotected eaves, soffits, and gutters; and unmanaged nearby fuels (trees, bushes, duff, accumulated dead natural fuels, firewood, and accumulated other combustible material and outbuildings) close to the building. Access may be problematic for fire vehicles and water supply may be inadequate for structural firefighting.

The compliant building is like the non-compliant building, except that it meets the requirements of the 2015 IWUIC. In summary, requirements of the 2015 IWUIC depend on the fire hazard severity and may include: non-combustible roofing material; fire-rated cladding; automatic sprinklers; underfloor and underdeck fire-rated enclosure; fire-rated glazing and exterior doors; non-combustible or protected gutters; non-combustible or protected eaves and soffits; and a defensible space created within a fuel modification distance from the structure, in which one must remove or manage trees, bushes, litter, duff, accumulated dead natural fuels, firewood, and accumulated other combustible material and outbuildings.

Fire experts use the term "response function" to mean what in this Interim Study is termed a "vulnerability function." Thompson et al. (2011) offer a number of response functions for various non-building assets and one class of building asset, which is labeled "cabin." The Thompson response functions for WUI fire risk were created using expert opinion and relate loss to flame length. The project team applied expert judgment and data on fire spread (TCLEE 2005) to modify the response function for cabins. The modifications represent the non-compliant and compliant buildings.

4.12 Estimating Property Repair Cost and Repair Duration

Property repair for a building or other asset subjected to excitation x is calculated as shown in Equation 4-23, where $L(x)$ is the property repair cost, j is an index to categories of property at the asset location (generally building, contents, or business stock), V_j is the value of one category of property at the asset, and $y_j(x)$ is the mean vulnerability function of that category of property evaluated at excitation x.

$$L(x) = V_j \cdot y_j(x)$$

(Equation 4-23)

The vulnerability functions for buildings produce as an intermediate product the probability $P_d(x)$ of various building damage states d occurring when the building is subjected to excitation x. Each damage state d is associated with a best estimate of the time required to repair the building from that damage state, denoted by t_d. The estimated repair duration is then calculated using the theorem of total probability, which states that the expected repair duration $t(x)$ is the sum of the products of $P_d(x)$ and t_d, summed over the number of possible damage states, denoted here by N_d. Equation 4-24 presents the calculation.

$$t(x) = \sum_{d=1}^{N_d} t_d \cdot P_d(x)$$

(Equation 4-24)

4.13 Residential Displacement Cost (Additional Living Expenses)

Residential displacement costs (which insurers call additional living expenses) are a function of displacement time or the length of time a residential structure is uninhabitable due to damage and costs related to the displacement. Housing costs are $1,500 per month for the length of displacement. Average rent in the United States according to the U.S. Census Bureau is $900; the analysis assumes $1,500 to account for higher costs as a result of housing market shifts or some households staying at hotels or other types of shelters including short-term public sheltering or long-term provision of mobile homes post-disaster. Adding $500/month for furniture rental and $100 per month for increased commuting costs produces a total monthly displacement cost of $2,100 per household. One can convert $2,100 per month per family to a daily cost per person by taking 1 month = 30.4 days (on average) and the average household size as 2.5 people. Thus, residential displacement can be estimated as ($2,100 per household per month) / (30.4 days per month) / (2.5 people per household) = $28 per person per day. Daily displacement cost for a household is ($2,100 per household per month) / (30.4 days per month) = $69 per household per day.

4.14 Estimating Business Interruption Loss

Consequences from natural or human-caused hazards, such as earthquakes, flooding, severe storms, droughts, terrorist attacks, industrial accidents, etc. include: damage (and direct disruptions) to physical and human capital (e.g., stock losses), and direct and indirect BIs, causing the loss of production and consumption (e.g., flow losses). Several studies have estimated total BI losses from disasters to be economically costlier than the direct losses, in cases such as 9/11 and Hurricane Katrina.

This project applies IO modeling for estimating indirect BI losses in the aftermath of disasters. An IO model is based on a tabulation of all purchases and sales in a given year between sectors of an economy and an assumption of a proportional relationship between inputs and outputs (Rose and Miernyk 1989). One of the strengths of the IO model is that it is supported by detailed data collected and compiled by national census and statistical agencies. In the United States, for example, extensive IO data are published by the BEA to generate the technical coefficient matrix that represents the proportional relationship between inputs and outputs (Miller and Blair 2009). This methodology is coupled with BEA's Regional Input-Output Multiplier System to provide a useful framework for evaluating economic interdependencies (U.S. Department of Commerce, 1997). These data are available from the BEA for the nation as a whole, each state, metropolitan regions (using the U.S. Census definitions), and counties. The availability of economic data enables the application of IO model and its hybrids for analysis of relatively small regions, e.g., infrastructure disruptions in Portland (Rose and Liao 2005).

Within the domain of IO modeling, the concept of inoperability has been used in recent studies to determine the direct and indirect economic losses in the aftermath of losses. Haimes and Jiang (2001) revisited the Leontief model and expanded it to account for inoperability, or the inability for sectors to meet demand for their output. The inoperability measure is a dimensionless number between 0 (ideal state) and 1 (total failure); and, as such, it is interpreted as the proportional extent in which a system is not functioning relative to its ideal state. Examples of studies that implemented Inoperability IO Model (IIM) to estimate economic losses include terrorism (Santos and Haimes 2004), electric power blackouts (Anderson et al. 2007), disease pandemics (Orsi and Santos 2010), and hurricane scenarios (Resurreccion and Santos 2013), among others.

Three general categories of data requirements that enable the implementation of the IIM are: (1) regional/geographic scope of the disaster, (2) extent to which the region is affected (e.g., scale of 0-100%), and (3) recovery period. The parameter descriptions of the IIM, as well as additional discussion on the dynamic model extensions, follow. Details of model derivation and an extensive discussion of model components are found in Santos and Haimes (2004) and also in Santos et al. (2008).

4.14.1 Model Parameters

The IIM is structurally similar to the classical IO model. The mathematical formulation is as follows:

$$q = A^{*}q + c^{*}$$

(Equation 4-25)

Where,

- q = the inoperability vector (e.g., the element, q_i, denotes the inoperability of sector *i*)
- A^{*} = the interdependency matrix (e.g., the element A^{*}_{ij} denotes the input requirement of sector *j* that comes sector *i*, normalized with respect to the total input requirements of sector *j*)

c^* = the demand perturbation vector (e.g., the element, c^*_i, denotes the demand perturbation to sector *i*)

4.14.2 Sector Inoperability

Inoperability is conceptually related to the term unreliability, which expresses the ratio with which a sector's production is degraded relative to some ideal or 'as-planned' production level. Sector inoperability (q) is an array comprised of multiple interdependent economic sectors. The inoperability of each sector represents the ratio of unrealized production (e.g., ideal production minus degraded production) relative to the ideal production level of the industry sectors. To understand the concept of inoperability, suppose that a given sector's ideal production output is worth $100. Suppose also that a natural disaster causes this sector's output to reduce to $90. The production loss is $10, which is 10% of the ideal production output. Hence, the inoperability of the sector is 0.10. Since a region is comprised of interacting sectors, the value of inoperability will further increase due to the subsequent ripple effects caused by sector interdependencies.

4.14.3 Interdependency Matrix

The interdependency matrix (A^*) is a transformation of the Leontief technical coefficient matrix (A), which is published by the BEA and is publicly available (BEA 2016). It is a square matrix with equal rows and columns, which correspond to the number of industry sectors. The elements in a particular row of the interdependency matrix can tell how much additional inoperability is contributed by a column industry sector to the row industry sector. When the interdependency matrix (A^*) is multiplied with the sector inoperability (q), this will generate the intermediate inoperability due to endogenous sector transactions. Endogenous transactions in the context of this Interim Study pertain to the flow of intermediate commodities and services within the intermediate sectors. These endogenous commodities and services are further processed by the intermediate sectors (e.g., commodities and services that are not further transformed or those used immediately for final consumption are excluded from endogenous transactions). The BEA's detailed IO matrices can be customized for desired geographic resolutions using regional multipliers, or location quotients based on sector-specific economic data. This process of regionalization is performed to generate region-specific interdependency matrices.

4.14.4 Demand Perturbation

The demand perturbation (c^*) is a vector comprising of final demand disruptions to each sector in the region. The demand perturbation, just like the inoperability variable in the IIM formulation, is normalized between 0 and 1. In this basic IIM formulation, supply disruptions are modeled as "forced" demand reductions. Consider a hypothetical disruption where the supply for a commodity or service decreases but demand remains virtually unaffected. In this case, the consumers will have to temporarily sacrifice their need for that commodity or service until it bounces back to its as planned supply level. The limitation of the basic IIM formulation is that it uses "forced" demand reduction as a surrogate to supply reduction. To address this shortcoming, the dynamic extension to the IIM was developed to enable a more explicit definition of perturbation parameters, in addition to the formulation of a sector-specific economic resilience matrix.[14]

[14] Economic resilience can be defined in many ways, here it refers to the ability to recover from the negative impacts of external economic shocks resulting from natural hazards.

4.14.5 Economic Resilience

A key motivation that led to the development of the dynamic IIM is the need for linking the concept of economic resilience with time-varying sector inoperability for a given recovery horizon. In general, resilience is defined as the ability or capability of a sector to absorb or cushion against damage or loss and rebound to the original state (Holling, 1973, Perrings, 2001). Rose and Liao (2005) suggest that *static* resilience can be enhanced through using existing resources as efficiently as possible, such as: 1) expedited restoration of the damaged capability; 2) using an existing back-up capability; 3) conservation of inputs to compensate for supply shortfalls; 4) substitution of inputs; or 5) shifting of production locations, among others; and that *dynamic* resilience is expedited through restoration of the damaged capability. Rose (2009) provides comprehensive definitions and categories of economic resilience including static, dynamic, inherent, and adaptive.

The dynamic formulation of the IIM takes into account the economic resilience of each sector, which influences the pace of recovery of the interdependent sectors in the aftermath of a disaster. The formulation is as follows:

$$q(t+1) = q(t) + K[A^*q(t) + c^*(t) - q(t)]$$

(Equation 4-26)

The term K is a sector resilience coefficient matrix that represents the rates at which sectors recover to their nominal levels of production following a disruption (Lian and Haimes 2006). The model dictates that the inoperability level at the following time step, $q(t+1)$, is equal to the inoperability at the previous stage, $q(t)$, plus the effects of the resilience of the sector. The values of K tend to be negative or zero, thereby detracting from the overall level of inoperability. As seen in the above equation, K is multiplied with the indirect inoperability resulting from other sectors, $A^*q(t)$, plus the degraded final demand, $c^*(t)$, minus the current level of inoperability, $q(t)$. The resilience coefficient, K, is assumed to be an inherent characteristic of a particular sector, but multiplying it with the inoperability product term, $A^*q(t)$, will result in coupled resilience across directly related sectors. This is particularly relevant when analyzing a sector that heavily depends on another sector for achieving its as-planned productivity levels. Regardless of how inherently resilient a sector is, its productivity will be significantly compromised when another sector it heavily depends on becomes largely inoperable in the aftermath of a disaster.

The dynamic extension answers one of the fundamental limitations of the basic IIM, which is the ability to capture time-varying recovery that adapts to some level of reasoning and current levels of inoperability within the perturbation and recovery period. For the dynamic extension to the IIM, Lian and Haimes (2006) provide the formulation to estimate the sector resilience coefficient of each sector. This resilience coefficient is a function of: 1) sector inoperability; 2) sector interdependencies; 3) recovery period; and 4) the desired level of inoperability reduction for the target recovery period. In this economic resilience formulation, economic resilience is inversely proportional to the recovery period. This is because resilience is a desired attribute of any system and, hence, a higher level of resilience is preferred. On the other hand, recovery period (e.g., the time it takes to reach full recovery) is desired to be at minimum to the extent possible. The higher the value of the sector resilience metric, the better equipped it is to protect and recover itself from external perturbations. Hence, increasing the economic resilience metric of a sector reduces its recovery period as well as the associated economic losses. The dynamic version of the IIM is capable of analyzing the extent to which sector resilience can decrease the magnitude of sector inoperabilities and economic losses, as well as shorten the recovery period. This formulation would create a time-dependent value to better account for the impact of different intensities and durations of a disaster, as longer ones would tend to further stress the sectors, adding to the BI losses and impacting their ability to recover. Lian et al. (2007), Santos (2006), Lian and Haimes (2006), and Haimes et al. (2005) applied the model to various regional disaster scenarios to analyze the recovery behaviors of critical economic sectors and infrastructure systems.

4.14.6 Economic Loss

Similar to sector inoperability, economic loss is an array comprised of multiple interdependent economic sectors. Each element in this array indicates the magnitude of economic (BI) loss of each sector, in monetary units (or particularly in U.S. dollars for the scenarios to be explored in the case studies). The economic loss of each sector is simply the product of the sector inoperability and the ideal production output. For example, an inoperability of 0.1 for a sector where production output is $100 will result in an economic (or production) loss of $10. Economic loss, in terms of decreased production or output, is treated as a separate disaster metric since it complements the inoperability metric. Both the inoperability and economic loss metrics are desired to be kept at minimum. It is also worth noting that when the sectors are ranked according to the magnitude of their inoperability and economic loss metrics, two distinct rankings will be generated. Suppose that a second sector has an inoperability of 0.2 and a production output of $40. The resulting economic loss will be 0.2*$40 = $8. Although the inoperability of the second sector (0.2) has a higher rank compared to the first sector (0.1), the direction of priority will reverse when economic loss is considered as the sole basis for ranking. Thus, the second sector has an economic loss of $8, which has a lower rank in contrast to the first sector’s $10 economic loss.

4.14.7 Relating Hazus Results with IO Assessment of Indirect Business Interruption

This Interim Study uses the results from various Hazus scenarios as inputs to assess the indirect BI losses. Disasters are expected to cause damage to various Hazus building occupancy classes. Hazus uses 33 building-occupancy classes categorized according to residential, commercial, industrial, religion/non-profit, educational, and government (28 if one ignores the differences between classes 3 through 8). See Table 4-25 for Hazus’ occupancy classes.

No.	Label	Occupancy class	Description
Residential			
1	RES1	Single-family dwelling	Detached house
2	RES2	Mobile home	Mobile home
3-8	RES3a-f	Multi-family dwelling	Apartment or condominium
9	RES4	Temporary lodging	Hotel/motel
10	RES5	Institutional dormitory	Group housing (military, college), jail
11	RES6	Nursing home	
Commercial			
12	COM1	Retail trade	Store
13	COM2	Wholesale trade	Warehouse
14	COM3	Personal and repair services	Service station/shop
15	COM4	Professional, technical services	Offices
16	COM5	Banks and financial institutions	
17	COM6	Hospital	
18	COM7	Medical office or clinic	Offices
19	COM8	Entertainment & recreation	Restaurants and bars
20	COM9	Theaters	Theaters
21	COM10	Parking	Garages
Industrial			
22	IND1	Heavy industry	Factory
23	IND2	Light industry	Factory
24	IND3	Food, drugs, chemicals	Factory
25	IND4	Metals, minerals processing	Factory
26	IND5	High technology	Factory
27	IND6	Construction	Office
Agriculture			
28	AGR1	Agriculture	
Religion/non-profit			
29	REL1	Church	
Government			
30	GOV1	General services	Office
31	GOV2	Emergency response	Police or fire station
Education			
32	EDU1	Schools	
33	EDU2	Colleges and universities	Does not include group housing

Table 4-25. Hazus building occupancy classes (FEMA 2012e).

For a particular disaster scenario, Hazus estimates several categories of losses (e.g., structural building loss, non-structural building loss, content loss, inventory loss, relocation loss, income loss, rent loss, and wage loss) in each occupancy class, expressed in annualized dollar loss. Nonetheless, it is important to extract only the direct BI (or direct flow) losses as inputs to the IO model. In subsequent discussions, the term *direct BI loss* refers to applicable direct flow loss categories (e.g., income loss, rent loss, and wage loss), while *indirect BI losses* represents the additional losses after the IO model is implemented.

From the perspective of IO modeling, the direct BI losses that can be extracted from Hazus will be interpreted as the direct flow loss to a particular building occupancy class, which further creates ripple effects to other business sectors due to their inherent interdependencies. Hence, in estimating the indirect BI losses, it is necessary to relate such occupancy classes with the equivalent economic sectors as used in the IO model. The first column of Table 4-26 contains the sector code created for the purpose of this Interim Study. The second column corresponds to the scope of the equivalent IO sectors as interpreted in a similar fashion as the annual IO accounts by the BEA. Finally, the last column of the table below contains the standard Hazus building occupancy class as described in previous sections of this Interim Study.

Code	Equivalent IO sector	Hazus occupancy
S1	Agriculture	AGR1
S2	Construction	IND6
S3	Other heavy industry	IND1
S4	Other light industry	IND2
S5	Food, drugs & chemicals	IND3
S6	Mining & metals/minerals processing & manufacturing	IND4
S7	High technology	IND5
S8	Wholesale trade	COM2
S9	Retail trade	COM1
S10	Banks & financial institutions	COM5
S11	Professional & technical services	COM4
S12	Education services	EDU1, EDU2
S13	Health services	COM6, COM7, RES6
S14	Entertainment & recreation	COM8, COM9
S15	Hotels	RES4
S16	Residential housing, other than hotels	RES1, RES2, RES3
S17	Other services	COM3, COM10
S18	Government & non-NAICS	GOV1, GOV2, REL1

Table 4-26. Relating IO sectors with Hazus occupancy classes.

After the direct effects of a disaster have been extracted from Hazus via the building occupancy class direct BI loss estimates, the indirect BI losses will be computed using the dynamic IO model. Recall that the dynamic IO formulation takes the form: $q(t+1) = q(t) + K[A^{*}q(t) + c^{*}(t) – q(t)]$.

It is important to note that not all perils investigated in the Interim Study utilized the Hazus software. For such cases, the direct BI losses were estimated from other data sources (see Appendix K.8 for details), and compared with sector-specific value-added data published by BEA. For example, the supply-use tables (BEA 2016) contain information on the applicable components of the value added (e.g., income and wage), which could be used to determine the magnitude of the direct BI loss relative to the output of each building occupancy class.

This Interim Study investigates the extent to which the term K in the dynamic IO formulation can be related to the concept of economic resilience. In particular, the aim of the BI loss analysis is to integrate two general types of inoperability. In the original dynamic inoperability IO model (DIIM), one assesses the inoperability of the sectors assuming that they are allowed to recover with no new additional perturbations. For tractability, a subscript '*DIIM*' is introduced to the left-hand side of the equation to generate the following revised formulation: $q_{DIIM}(t+1) = q(t) + K[A^{*}q(t) + c^{*}(t) - q(t)]$.

The subscript 'NEW' will be introduced to the left-hand side of the dynamic equation to represent a new level of perturbation (e.g., a resilience tactic can reduce the impact of a disaster on a sector's inoperability). One can rewrite this new dynamic equation as follows: $q_{NEW}(t+1) = q(t) + K[A^{*}q(t) + c^{*}(t) - q(t)]$. It can be shown that the expected value of the inoperability at t+1 can be formulated directly from the event tree as depicted in the figure on the right, which is a simplified representation of the event tree inoperability model. Sample representations of the sequential inoperability event trees for hypothetical baseline and mitigated scenarios are shown below.

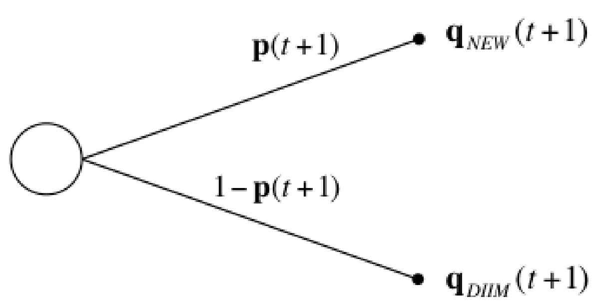


Figure 4-17. Event tree for inoperability decomposition.

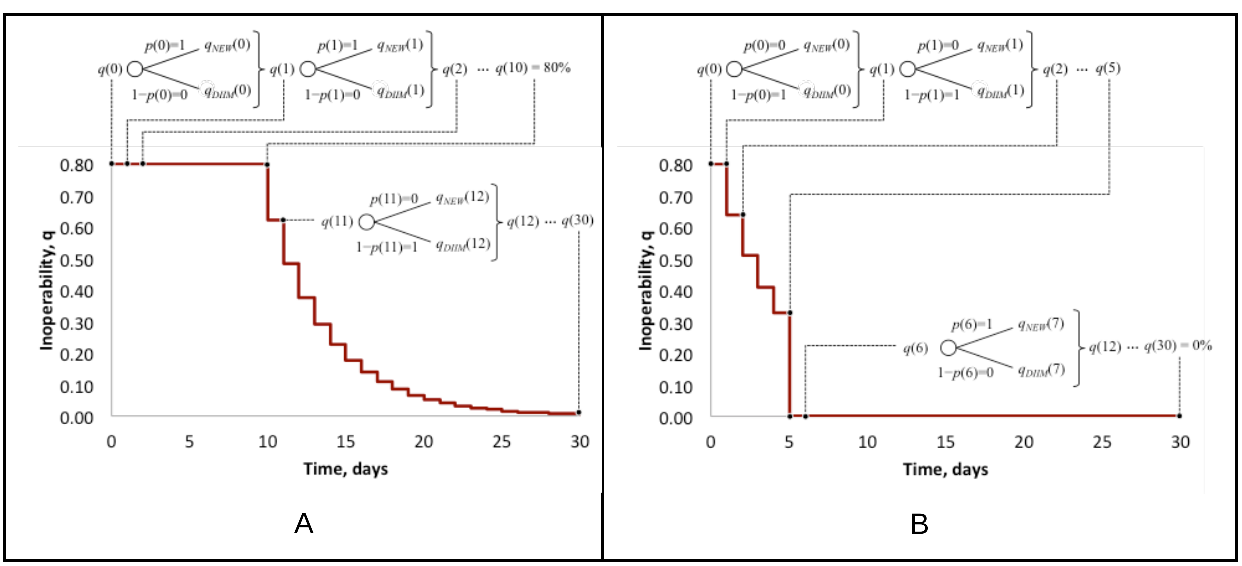


Figure 4-18. Inoperability event trees: A) sample baseline scenario, B) mitigated scenario.

At time $t = 0$, the sector inoperability $q(0)$ will be directly linked to direct BI loss for each building occupancy class from Hazus. The dynamic equation then computes for the progression of indirect BI losses over time due to sector interdependencies. This Interim Study investigates the extent to which various resilience strategies can potentially decrease the magnitude of economic losses in each sector over time. For example, Rose (2009) has introduced the term static economic resilience as "the efficient use of remaining resources at a given point in time." Furthermore, Rose defines dynamic economic resilience as "accelerating the pace of recovery." In this Interim Study, the focus is on the following types of static economic resilience tactics: 1) production recapture; 2) inventories; 3) facility relocation; and 4) excess capacity. In subsequent discussions, the process for integrating the resilience tactics with the IO model is explained.

Within the IO framework, there are various types of economic multipliers that can provide insights in measuring the extent to which a change in an economic activity (e.g., consumption or production) of a sector can cascade to other dependent sectors. For example, the output multipliers published by BEA measure the expected changes in the output of various sectors given a $1 change in the demand for a particular sector. Nonetheless, such multipliers often do not take into consideration the resilience attributes of the economic sectors. As a hypothetical example, suppose that the output multiplier for sector *i* is 2.30 for every unit change in the demand for sector *j*. This implies that if the demand for sector *j* were to grow by an amount of $1, the *indirect* output in sector *j* would grow by an additional $1.30. Note that this logic does not symmetrically apply for the case of demand reduction because the economic sectors have their static resilience attributes, hence avoiding the scenario of incurring the maximum possible loss.

Since IO multipliers are typically computed using annual data, the maximum possible loss is assumed to be distributed across a period of 1 year (although this baseline annual recovery horizon may be adjusted for disasters that require longer recovery). Without resilience, the loss is assumed to be at its greatest immediately after a disaster and exponentially dissipates over time, which as implied by the dynamic IO formulation, takes the form: $q(t+1) = q(t) + K[A^*q(t) + c^*(t) - q(t)]$.

In modeling the indirect BI loss using the IO framework, the approach is to assess the extent to which each static resilience tactic can avoid operating at the maximum possible loss. The four resilience tactics specifically considered in this Interim Study and their descriptions, directly adapted from Rose (2009), are summarized as follows:

- **Production recapture**: refers to working overtime or extra shifts to recoup lost production
- **Inventory**: include both emergency stockpiles and ordinary working supplies of production inputs
- **Relocation**: changing the site of a business activity
- **Excess capacity**: refers to using idle plant and equipment

The key steps in performing the indirect BI loss methodology are enumerated below.

Step 1. Obtain the direct BI loss estimates for each Hazus building occupancy class, and compute the corresponding direct losses to the IO sectors using the relationship mapping given in Table 4-26. To generalize the process, a $1 direct BI loss to each occupancy class can be arbitrarily assumed to determine the corresponding direct BI loss to the applicable IO sectors.

Step 2. Using standard IO multiplier analysis, estimate the maximum possible indirect BI losses that can be experienced by the dependent economic sectors given the direct BI loss obtained from Step 1. Then, allocate (or spread) the maximum possible loss over a recovery period of 1 year. As noted earlier, the assumed annual recovery period can be adjusted depending on the severity of the disaster.

Step 3. Compute the avoided losses for each of the resilience tactics across the recovery period, relative to the maximum possible indirect BI losses obtained from Step 2. The difference between maximum and avoided losses will be considered as the indirect BI loss multiplier for each sector. The supporting data and assumptions on the efficacy of each resilience tactic in curbing the losses are shown in Table 4-27.

Step 4. Using the building-sector relationship mapping, trace back the corresponding indirect BI loss multiplier for each Hazus occupancy class.

There are 33 building occupancy classes in Hazus. Figure 4-18 shows the indirect BI loss generated for every $1worth of direct loss to each occupancy class, taking into account the avoided losses due to the four resilience tactics. It can be observed that the building occupancy classes have varying levels of resilience. For example, approximately 40 cents worth of indirect BI loss is generated for every $1worth of direct loss to the residential buildings. Metals processing, professional services, and banks appear to be highly resilient since they generate low indirect BI losses. In contrast, the entertainment sectors (e.g., movie theaters) appear to be relatively less resilient since they generate high indirect BI losses. Similar analysis can be performed for the remaining building occupancy classes. The values of the indirect BI loss multipliers for each building occupancy class are found in Section 4.12 and also Appendix K of this Interim Study.

Tactic	Data sources	Assumptions
Production Recapture	Chapter 15 of the Hazus manual (FEMA 2012e) shows the recapture rates for various occupancy classes. In particular, the project team used the output recapture factors found in the last column of Table 15.14 in the Hazus manual.	It was assumed that production recapture is highest during the first 90 days, and then decays by a factor of 25% in subsequent quarters as increasingly more customers cancel their orders and seek alternative suppliers. It was also assumed that production recapture reaches a value of 0 at the end of year 1 (e.g., production loss will not be recaptured at end of year 1 and thereafter).
Inventories	The U.S. Census Bureau publishes inventory-to-sales ratios (ISR) for various economic sectors. The following link gives up-to-date ISR data for various manufacturing and trade sectors.[15]	Typically, ISR values are greater than 1. The ideal case is when ISR = 1, in which 100% of the production is sold within a given period. In contrast to just-in-time concepts, inventories may have an advantage in times of disasters. They can be used as buffers when production is disrupted in the aftermath of a disaster. The efficacy of inventories depend on the magnitude of the ISR and also the rate with which they get depleted as the disaster progresses over time.
Relocation	The possibility of relocating a particular building occupancy class can be implicitly derived from relevant data found in the Hazus manual. In particular, Table 15.10 of the Hazus Technical Manual gives the building recovery times for various damage scenarios.	The building recovery times are provided for different structural damage scenarios (none, slight, moderate, extensive, and complete). Each building occupancy class has data on recovery time (in days). The tipping point on whether to relocate or not is based on the moderate damage scenario. Hence, losses associated with exceeding the recovery times for the moderate scenario are assumed to be avoidable via relocation.
Excess Capacity	Excess capacity is based on Table 15.11 of the Hazus Technical Manual, which gives the building service interruption multipliers.	The building service interruption multipliers are also given for each building occupancy class for various structural damage scenarios (none, slight, moderate, extensive, and complete). It is assumed that service interruption multipliers that are relatively lower are associated with buildings that have higher excess capacity.

Table 4-27. Data sources and assumptions for the four resilience tactics.

[15] See https://www.census.gov/mtis/index.html for more information.

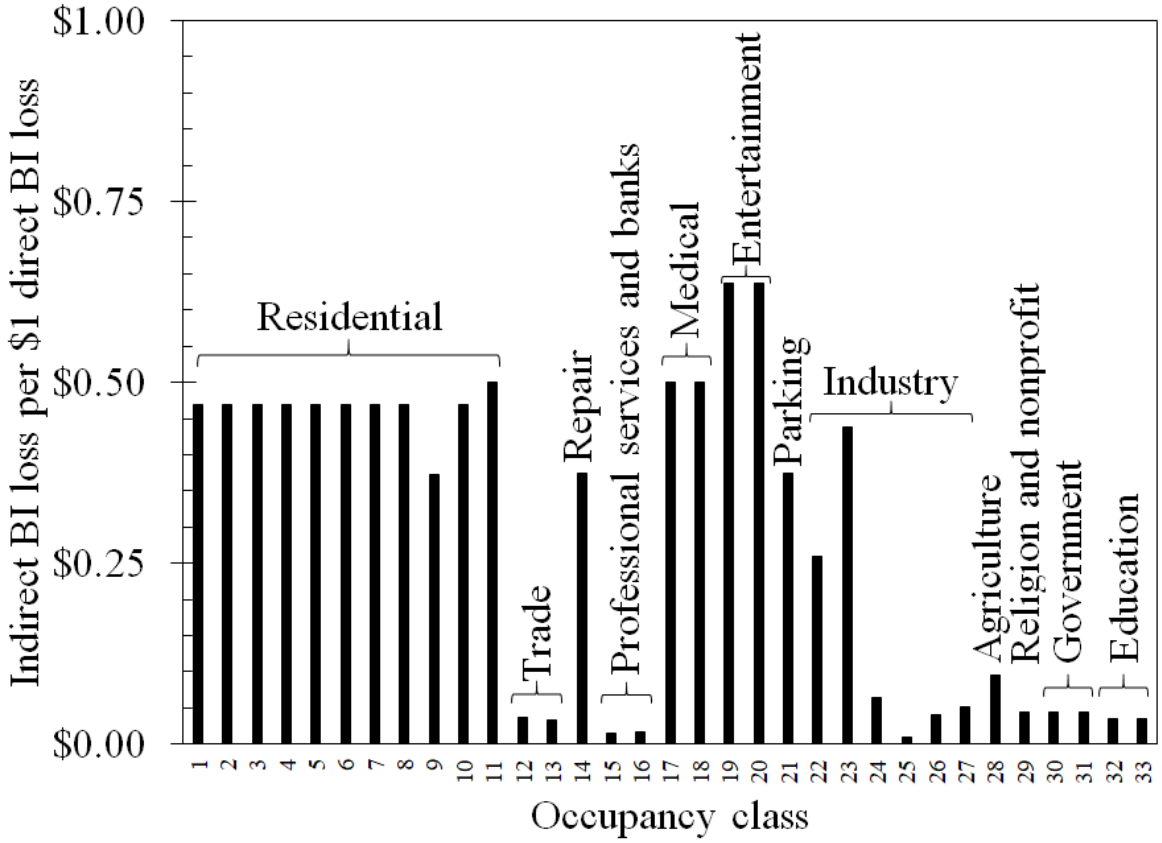


Figure 4-19. Indirect BI loss for every $1 of direct BI loss in each Hazus building occupancy class.

4.14.8 Additional Considerations in Estimating Business Interruption Losses

Disasters can cause severe damage to existing infrastructure, consequently affecting economic productivity. Temporary closure of factories and stores, loss of mobility (e.g., due to flooding and debris cleanup), and damage to infrastructure systems, among others, can drastically affect workforce and commodity flows for prolonged periods of time. Reduction in worker flow decreases productivity, and reduction in commodity flow results in cascading demand and supply impacts. Using detailed journey-to-work data, commodity flow surveys, and social accounting matrices allows modeling of disruptions to regional productivity. Modeling efforts include the potential for cascading failure, accounting for spatial dependencies and various economic and social travel patterns.

In the aftermath of a disaster, a region expects substantial disruptions to infrastructure capacity, workforce availability, and mobility. These direct disruptions in turn can trigger sector productivity degradations indirectly to all sectors of the economy. The project team collected and assembled economic data (such as input requirements, commodity outputs, and income statistics, among others) from different sources in order to quantify the impact of reduced sector productivity levels on the economy of the affected region. These data are key to calibrating the models used in this Interim Study and to simulating potential direct and indirect BI losses from various perils with and without mitigation. The BI losses prevented are potentially a major source of benefits of mitigation.

4.15 Estimating Total (Direct and Indirect) Business Interruption Loss

In some cases, the project team used Hazus and FEMA's BCA Tool to estimate BI losses. The Hazus flood module (release 3.2) was found to have a bug that underestimates direct BI loss by a factor of 100, so where that tool is used (in the analysis of the cost-effectiveness of federally funded grants), one can compensate for the bug by multiplying direct BI losses by 100. In the case of designing to exceed the 2015 I-Code requirements for earthquake, wind, and flood, Hazus and the BCA Tool do not apply, so the project team used the following procedures.

Rental and BI costs vary widely. Hazus offers some very old (1994) rental and disruption costs and warns that costs vary widely geographically; Therefore, it is important to revisit these amounts. For residential occupancies RES1 through RES3 and RES5, it is assumed that monthly household furniture, higher commute costs, and miscellaneous other costs of $600/month/household, monthly house rental cost of $1500/month/household, and 2.5 people per household (OECD 2015), suggesting $28/person/day or $70/household/day. For temporary lodging (RES4), assume lost revenue and wages equal to a typical average per-night hotel cost of $125 per day. For nursing homes (RES6), assume lost revenue and wages equal to the average daily cost of a private room in a nursing home, $248 per day (Mullin 2013). For nonresidential occupancies, the project team estimated output loss (direct BI loss) per day of downtime as the ratio of industry wages and earnings to number of employees, converted to dollars per day. Results are shown in Table 4-28.

For indirect BI, one can use IO analysis to estimate the per-dollar indirect BI loss Q resulting from $1.00 of direct BI in a given occupancy class. See Section 4.14 for details. One can calculate Q for each occupancy class by setting the output loss for that occupancy class to $1.00 and the output losses for all the other occupancy classes to 0. For example, to calculate Q for RES3 occupancy, set the output losses for RES1, RES2, RES4, and EDU2 to 0, and the output loss for RES3 to 1.0. The resulting indirect BI to the entire economy can then be assigned to Q for RES3. Thus, given the time t required to restore a facility to functionality, the total BI loss per occupant L_{BI} (direct and indirect) can be calculated as shown in Equation 4-27.

$$L_{BI} = V_{BI} \cdot (1 + Q) \cdot t$$

(Equation 4-27)

No.	Occupancy Class	Label	V_{BI}	Q
1	Single-family dwelling	RES1	$ 28.00	0.470
2	Mobile home	RES2	$ 28.00	0.470
3	Multi-family dwelling	RES3a	$ 28.00	0.470
4	Multi-family dwelling	RES3b	$ 28.00	0.470
5	Multi-family dwelling	RES3c	$ 28.00	0.470
6	Multi-family dwelling	RES3d	$ 28.00	0.470
7	Multi-family dwelling	RES3e	$ 28.00	0.470
8	Multi-family dwelling	RES3f	$ 28.00	0.470
9	Temporary lodging	RES4	$125.00	0.372
10	Institutional dormitory	RES5	$ 28.00	0.470
11	Nursing home	RES6	$248.00	0.500
12	Retail trade	COM1	$132.28	0.037
13	Wholesale trade	COM2	$295.21	0.033
14	Personal and repair services	COM3	$166.77	0.374
15	Professional/technical services	COM4	$414.93	0.016
16	Banks/financial institutions	COM5	$411.00	0.017
17	Hospital	COM6	$243.60	0.500
18	Medical office/clinic	COM7	$237.82	0.500
19	Entertainment & recreation	COM8	$118.94	0.637
20	Theaters	COM9	$118.94	0.637
21	Parking	COM10	$118.94	0.374
22	Heavy industry	IND1	$312.49	0.260
23	Light industry	IND2	$242.04	0.438
24	Food, drugs, chemicals	IND3	$203.04	0.064
25	Metals and minerals processing	IND4	$233.26	0.009
26	High technology	IND5	$465.98	0.041
27	Construction	IND6	$228.35	0.051
28	Agriculture	AGR1	$124.43	0.095
29	Church	REL1	$165.50	0.045
30	General services	GOV1	$230.28	0.045
31	Emergency response	GOV2	$230.28	0.045
32	Schools	EDU1	$162.11	0.035
33	Colleges and universities	EDU2	$162.11	0.035

Table 4-28. Output loss per day of downtime V_{BI} and per-dollar indirect BI loss Q.

4.16 Insurance Benefits

Property damage and time-element losses may be covered by insurance, especially in the case of fire damage, less so for wind and flood damage, and even less for earthquake insurance. Natural hazard mitigation can be expected to reduce natural hazard insurance losses, and in many cases the insurer reduces premiums to account for the lower risk. The property owner or other insured benefits from lower risk because his or her premiums are reduced. However, in the presence of insurance, the property owner or other insured also recovers part of the premium paid in the form of insurance claims. Thus, the benefit to the insured is just part of the reduced amount of the insurance premium: the part that the insured pays in excess of the expected value of claims, loosely termed overhead for a nonprofit insurer or O&P for a for-profit insurer. A portion of the excess amount is roughly proportional to the expected value of claims. That portion drops as the expected value of claims drops. The reduction can be counted as a benefit.

One can therefore estimate the benefit of reduced O&P using Equations (4-28) and 4-29).

$$y = \frac{P - C}{C}$$

(Equation 4-28)

$$B = y \cdot \left(EAL - EAL' \right)$$

(Equation 4-29)

Where,

B = annual dollar benefit of reduced insurance premiums to a particular insured
P = premiums and other costs paid by insureds, excluding fixed costs
C = expected value of annual claims paid to or on behalf of all insureds
EAL = as-is expected annualized loss to the particular insured undertaking mitigation
EAL' = what-if expected annualized loss to the particular insured undertaking mitigation
y = fraction of *P* in excess of *C*, e.g., the average variable portion of premiums contributing to insurer's overhead and profit costs

In the case of the NFIP, FEMA provides times series for *P* and *C*.[16] The time series for P exclude certain costs to the insureds: federal policy fees, reserve fund assessments, Homeowner Flood Insurance Affordability Act (HFIAA) surcharges, and probation surcharges. Of these, the reserve fund assessment scales with risk. In 2016, the reserve fund assessment totaled $0.495 billion, which amounts to 15% of $3.370 billion in net written premium (T. Hayes, FEMA Chief Actuary, written communication, 11 Apr 2017). Therefore 15% is added to each value of net written premium in the time series to estimate *P*. Figure 4-20 plots accumulated values y from 1978 to present day. The final value of *y*, averaging over all 38 years of *y*-data, is 0.17, a relatively low amount compared with commercial insurers, because the NFIP does not have to produce a profit and because it incurs no reinsurance costs, the reinsurer effectively being the U.S. Treasury. Bear in mind that the 0.17 figure excludes fees, assessments, and surcharges that do not scale with risk. See Box 4-3 for a restatement of insurance benefit.

[16] To learn more, visit: https://www.fema.gov/statistics-calendar-year.

Box 4-3. Clarifying Insurance Benefits

Insurance savings are only attributable to the reduction in the portion of insurance premiums associated with administrative costs. Consider: if one builds an insured house to a higher standard, building repair costs go down, but that savings can only be counted once. If the property is insured, the insurer pays the repair costs, but those costs are completely offset in the long run by a portion of the premiums that the property owner has paid. (That portion is called *pure premium*.) Otherwise, the property owner pays the repair costs. One way or another, the property owner pays for the repairs, either through pure premium, which passes through the insurer, or directly to contractors. But the property owner also pays for the insurer's administrative costs (in the case of NFIP), or O&P (in the case of private insurance). In the case of NFIP, the administrative costs amount to a factor of about 0.17 times the pure premium. Private insurance has a higher ratio of O&P to pure premium, about 0.42. That is, the property owner pays total NFIP premiums and fees of about 1.17 times the pure premium, or about 1.17 times what the property owner could expect to pay, on average, over the long term, to repair damage, or 1.42 for private insurance.

Assume that in the long run, on an overall average, insurance is priced so that the average insured pays the same factor for administrative cost, regardless of whether the property is built to code or above code. That is, assume insurance is priced properly, in proportion to pure premium. The reduction in administrative costs or O&P scales with the reduction in building repair costs. Reduce repair costs by $100 and one reduces NFIP administrative costs by $17 or private insurance O&P by $42. Therefore, one can estimate the insurance benefit as a factor of property loss reduction.

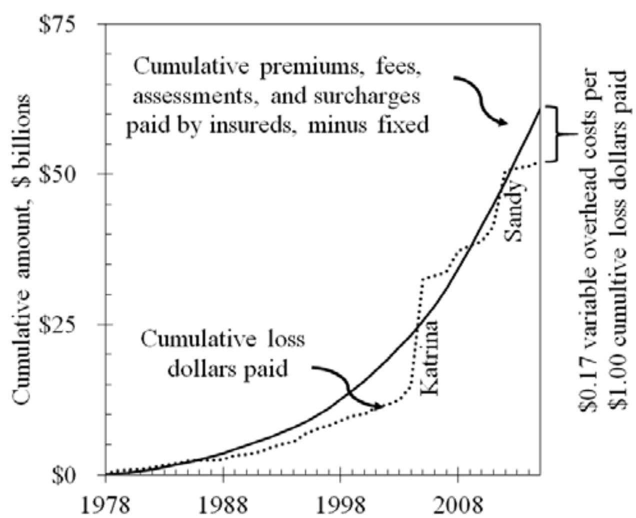


Figure 4-20. Overhead factor y for NFIP flood insurance.

Here are the implications of Equation 4-29: One expects B to fluctuate over short periods of time but to stabilize over the long run. One expects the policyholder's benefit to be highest in years when NFIP is profitable, e.g., when there are no big catastrophes, because NFIP's revenues in excess of losses come out of the policyholder's premiums and other fees, assessments, and surcharges. The space between the dotted and solid lines in Figure 3-5 is y, which is proportional to benefit. It is largest in years without a big catastrophe, as one would expect. One expects the policyholder's benefit to drop in years when a big catastrophe occurs, because NFIP's revenues in excess of losses are lower or negative in that year. That may seem counterintuitive, but remember that less NFIP excess revenue means less savings to the policyholder, again because NFIP excess revenue comes out of the policyholder's pocket. That is what Figure 4-20 shows: smaller or negative values of y appear around Hurricanes Katrina (2005) and Sandy (2012).

4.17 Deaths, Nonfatal Injuries, and Post-Rraumatic Stress Disorder

4.17.1 Deaths and Nonfatal Injuries

The 2005 *Mitigation Saves* study considered many ways to assign an economic value to human health. (See that work for several options and their advantages and disadvantages.) As in 2005, the 2017 project team valued human health as the DOT's acceptable cost to avoid a statistical injury.[17] By that approach, a 2015 regulation that prevents injuries would be deemed cost-effective if it cost less than $9.4 million per statistical fatality avoided, and lesser amounts for lesser injuries, in the proportions shown in Table 4-29. Table 4-30 expresses the acceptable costs to avoid statistical injuries, in terms of Hazus injury severity levels. The 2017 project team mapped from AIS to Hazus injury levels the same way as in the 2005 *Mitigation Saves* study. Note that a statistical fatality refers to the death of an unknown person at some unknown time in the future, not the death of a particular person in peril at the present time or the death of a particular person in the past.

AIS level[(a)]	Severity	Fraction of VSFA[(b)]
AIS 1	Minor	0.0020
AIS 2	Moderate	0.0155
AIS 3	Serious	0.0575
AIS 4	Severe	0.1875
AIS 5	Critical	0.7625
AIS 6	Fatal	1.0000

(a) AIS refers to the abbreviated injury scale used by the Association for the Advancement of Automotive Medicine (2001) and (b) VSFA refers to the acceptable cost to avoid a statistical fatality ($9.5 million in the third quarter of 2016, using the GDP implicit price deflator from Federal Reserve Bank of St. Louis).

Table 4-29. Acceptable cost to avoid a statistical injury, with injuries measured by AIS.

[17] To learn more, visit: https://www.transportation.gov/sites/dot.gov/files/docs/VSL2015_0.pdf.

Severity	Fraction of VSFA	Cost (2016 $)	Comment
Hazus 1	0.0056	53,000	Geometric mean of AIS 1 and 2
Hazus 2	0.0575	550,000	Same as AIS 3
Hazus 3	0.3781	3,700,000	Geometric mean of AIS 4 and 5
Hazus 4	1.0000	9,500,000	Same as AIS 6

Table 4-30. Acceptable cost to avoid a statistical injury, with injuries measured by Hazus injury severity.

To apply these values in calculating EAL, the acceptable cost to avoid a statistical injury is calculated using Equation 4-30, in which N denotes the mean number of people in the asset at an arbitrary time of day, j is an index to injury severity, V_j denotes the acceptable cost to avoid a statistical injury of severity j, and $y_j(x)$ denotes the mean fraction of occupants who experience injury severity j when the asset experiences excitation x.

$$L(x) = N \cdot \sum_j V_j \cdot y_j(x)$$

(Equation 4-30)

4.17.2 Post-Traumatic Stress Disorder (PTSD)

Considering the time frame of this project, the best approach to include costs and benefits related to reducing PTSD is a simplified method based on Sutley et al. (2016a). Based on this work and others on PTSD after disasters, the project team used AIS level 3 or Hazus injury severity 2 as a proxy for rates of PTSD in a community. That is, one takes the number of people who are estimated to experience PTSD as equal to the number who are estimated to experience Hazus injury severity 3. (See Table 4-30 for the relationship between AIS and Hazus injury severity.)

The likelihood of a person experiencing PTSD is clearly impacted by the person's socioeconomic status but, for practical reasons, this analysis does not adjust for socioeconomic status. As reflected in the work by Sutley et al. (2016a), rates of PTSD are higher among children, the elderly, racial and ethnic minorities, single parents, women, and the poor. By not modifying the proxy measure of PTSD by these factors, this method takes a conservative approach to including these costs and benefits.

The project team considered the cost of mental health impacts similarly to costs related to injuries as a whole, that is, as an acceptable cost to avoid a future statistical injury, as opposed to the expense associated with a particular injury. The costs consider direct treatment costs where treatment is about 10% of the overall costs of the incidence, and the other costs include things like lost wages, lost household productivity, and pain and suffering. In 2008, as the result of a two-year study, RAND estimated the cost to treat PTSD in military personnel to be between $5,900 and $10,300. With co-morbidities such as depression, the cost can be significantly higher ($16,890) (Tanielian and Jaycox 2008). These costs would be higher still if the length of their study were longer, as those authors note. The present Interim Study uses $9,000 for direct treatment costs and $90,000 for the overall acceptable cost to avoid a statistical incidence of PTSD. As reported in the 2005 *Mitigation Saves* study, 10% of the costs of an injury are considered direct medical costs, with the remaining value other costs as highlighted above. The $90,000 is consistent with this documented approach.

Because few BCAs even attempt to include these costs, the addition of acceptable costs to avoid a statistical instance of PTSD is a conservative but innovative addition to the 2017 *Mitigation Saves* study. The acceptable cost to avoid incidents of PTSD is estimated using Equation 4-30, where N denotes the number of people estimated to experience PTSD and V_{PTSD}, the acceptable cost to avoid a single incident, is taken as $90,000.

4.17.3 Discounting Human Life, Nonfatal Injuries, and PTSD

As in the 2005 *Mitigation Saves* study, the present Interim Study does not apply the time value of money to discount human deaths, nonfatal injuries, and PTSD. Instead, it values an injury avoided some years hence equal to an injury avoided 1 year hence, and recognizes avoided injuries over the useful life of a mitigation project or a building. The rationale, briefly, is that 1) there are actual financial instruments and measures of the time value of money, but no equivalent indices for human life, and 2) a reduction ad absurdum argument: if one applies a monetary discount rate to human life—any positive discount rate—one must accept that there is a duration of time where the cost of a cup of coffee today is somehow greater in value than a million human lives in the future. Since the conclusion appears morally untenable, one can reject the premise. Standard practices differ from agency to agency. For example, the value of a statistical fatality avoided (VSFA) differs between sources. Since this is an independent Interim Study, the project team applied its own judgment of what constitutes best practice, including whether and how to apply a discount rate to human safety.

4.18 Other Intangibles

Other intangibles addressed in the 2005 study tended to contribute a relatively small amount to the benefits. (For additional details on this approach, consult Appendix J of the 2005 report.) The loss of intangibles such as historical buildings and environmental damage are valued with benefit-estimate-transfer approaches. These vary by the type of benefit to be recognized: recreational water quality; drinking water; outdoor recreation trips; hazardous waste; wetlands; aesthetics; health and safety benefits from underground power lines; and cultural and historical resources.

4.19 Estimating Expected Annualized Losses

The expected annualized loss (*EAL*) from any given loss category (property loss, BI, etc.) is calculated as shown in Equation 4-31. In the equation, $G(x)$ denotes the mean annual rate of exceeding excitation x.

$$EAL = \int_{x=0}^{\infty} L(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation 4-31)

For earthquake risk, $L(x)$ is taken as piecewise linear with x and $ln(G(x))$ as piecewise linear with x, in which case one can perform the integration exactly, as shown in Appendix K.18, Equation K-60. For other perils, one can evaluate Equation 4-31 numerically, generally as shown in

Equation 4-32. One generally knows the excitation *x* and its mean recurrence interval *MRI* at *N* increments. For example, the project team estimated the coastal wind hazard at $N = 6$ mean recurrence intervals of 10, 50, 100, 300, 700, and 1,700 years. In the equation, $G = 1/MRI$.

$$EAL \approx \left(\sum_{i=0}^{N-2} L(x_i) \cdot (G_i - G_{i+1}) \right) + L(x_{N-1}) \cdot G_{N-1}$$

(Equation 4-32)

4.20 Estimating and Aggregating Benefits and Costs to the National Level

4.20.1 Aggregating Above-Code Design Results by Peril to the National Level

Common approach. For each peril and location, the project team estimated an IEMax design level as discussed in Section 4.5. In cases where designing to exceed I-Code requirements is not cost-effective, the project team took the IEMax level as current design practice. In all cases, "current design practice" means complying with the requirements of the 2015 I-Codes (IBC or IRC, as appropriate). In the case of fire at the WUI, "current design practice" means no requirement to comply with the 2015 IWUIC, except insofar as the IBC makes the same requirements. For each peril, nationwide BCR is calculated as follows:

$$B_{A,p} = \sum_{o} I_o \left(\sum_{m} \left(\Delta EAL_{m,res,o} \cdot \frac{(1 - e^{-r_{res} \cdot t})}{r_{res}} + \Delta EAL_{m,nres,o} \cdot \frac{(1 - e^{-r_{nres} \cdot t})}{r_{nres}} \right) + \sum_{i} \Delta EAL_{i,o} \cdot t \right)$$

(Equation 4-33)

$$C_{A,p} = \sum_{o} I_o \cdot C_o$$

(Equation 4-34)

$$BCR_{A,p} = \frac{B_{A,p}}{C_{A,p}}$$

(Equation 4-35)

Where,

$B_{A,p}$ = nationwide benefit of designing above (*A*) I-Code requirements for a given peril *p* (flood, wind, earthquake or fire)

$BCR_{A,p}$ = nationwide BCR of designing above (*A*) I-Code requirements for a given peril *p* (flood, wind, earthquake or fire)

$C_{A,p}$ = nationwide cost of designing above (*A*) I-Code requirements for the given peril *p*

C_o = additional cost to design and build all properties in location *o* to the IEMax level exceeding I-Code requirements in that location (the subscripts *A* and *p* are omitted for brevity)

$\Delta EAL_{m,res,o}$ = reduction in expected annualized loss for monetary benefit category *m*, all residential properties in location o, assuming all such properties are designed to the IEMax level of design to exceed I-Code requirements

$\Delta EAL_{m,nres,o}$ = reduction in expected annualized loss for monetary benefit category *m*, all nonresidential properties in location *o*, assuming all such properties are designed to the IEMax level of design to exceed I-Code requirements

$\Delta EAL_{i,o}$ = reduction in expected annualized loss associated with casualties and PTSD of category *i* in location *o*, assuming all properties are designed to the IEMax level of design to exceed I-Code requirements

i = index to categories of human injuries and PTSD (e.g., Hazus injury severities 1, 2, 3, and 4, and PTSD)

I_o = an indicator function: 1 if designing to exceed I-Code requirements is cost-effective at location *o*, 0 otherwise

m = an index to monetary benefit categories: building and content repair costs, direct and indirect BI costs, environmental benefits, preservation of historical value

o = index to locations, e.g., counties for earthquake, wind speed bands for wind, etc.

r_{res} = discount rate for residential properties; see Appendix H for value

r_{nres} = discount rate for nonresidential properties; see Appendix H for value

t = duration over which the benefits are to be recognized; the present Interim Study uses *t* = 75 years; see Appendix I for rationale.

Earthquake. In the case of earthquake, locations are indexed by county. The IEMax design level is the highest value of I_e where the ratio of incremental benefit to incremental cost exceeds 1.0 in that county, as in Section 4.5. In cases where designing to exceed I-Code requirements is not cost-effective, the IEMax level is I_e = 1.0, that is, code-level design.

Wind: In the case of hurricane wind, locations are indexed by ASCE 7-16 wind bands, and by a distance to coast band of 1 mile to delineate IBHS FORTIFIED Home Hurricane requirements. The IEMax design level is the corresponding IBHS FORTIFIED Home program where the ratio of incremental benefit to incremental cost exceeds 1.0, as in Section 4.5. In cases where designing to exceed I-Code requirements is not cost-effective, the IEMax level is baseline IRC requirements, that is, code-level design.

Coastal surge: In the case of coastal surge, locations are indexed by ASCE 7-16 wind bands and by state. The IEMax design level is the corresponding incremental building elevation where the ratio of incremental benefit to incremental cost exceeds 1.0, as in Section 4.5.

Riverine and coastal flood. The IEMax level is measured at a small geographic level with the highest value of floor elevation above BFE where the ratio of incremental benefit to incremental cost exceeds 1.0, as in Section 4.5. In cases where building above BFE + 1 foot is not cost-effective, the IEMax level is BFE + 1 foot, that is, code-level design.

Fire. For fire at the WUI, that IEMax level is measured at a smaller geographic level with the binary variable: is it cost-effective to adopt the 2015 IWUIC, yes or no?

4.20.2 Aggregating Federal Grant Results by Peril to the National Level

Common approach. For each peril, hazard stratum, and sample project, the project team calculated the reduced EAL by benefit category (generally building damage, content damage, direct BI, indirect BI, casualties, PTSD, environmental value, historical value). The project team estimated the project benefit b_o using Equation 4-36 and the project-level BCR using Equation 4-37.

$$b_o = \left(\sum_m \left(\Delta EAL_m \cdot \frac{(1 - e^{-r \cdot t})}{r} \right) + \sum_i \Delta EAL_i \cdot t \right)$$

(Equation 4-36)

$$bcr_o = \frac{b_o}{c_o}$$

(Equation 4-37)

Where,

b_o = benefit of mitigation investment for project *o*
c_o = mitigation cost of project *o*
bcr_o = BCR for project *o*

Two indices *h* and *p* to bcr_o indicate the hazard level *h* (low, medium, or high) and the peril *p* that the grant mitigates. One can aggregate benefits from all U.S. government-funded mitigation grants for the given peril to the national level using Equation 4-38, the nationwide total cost of all projects for the given peril using Equation 4-39, and the overall nationwide BCR for the given peril using Equation 4-40.

$$B_{G,p} \approx \sum_h \left(C_{6A,h,p} \cdot \left(\frac{1}{n_{6,h,p}} \sum_{o_{h,p}} bcr_{o,h,p} \right) \right)$$

(Equation 4-38)

$$C_{G,p} = \sum_h C_{G,h,p}$$

(Equation 4-39)

$$BCR_{G,p} = \frac{B_{G,p}}{C_{G,p}}$$

(Equation 4-40)

Where,

$B_{G,p}$ = nationwide benefit of all government-funded mitigation grants (G) for the given peril p, whether sampled or not
$BCR_{G,p}$ = nationwide BCR for all government-funded mitigation grants (G) for the given peril p
$bcr_{o,h,p}$ = BCR for sample o within hazard level h in the given peril p (Equation 3-36)
$C_{G,p}$ = cost of all government-funded mitigation grants (G) for the given peril p
$C_{G,h,p}$ = cost of all grant-funded projects in peril p, hazard stratum h, whether sampled or not
h = index to hazard levels (low, medium, high)
$n_{G,h,p}$ = number of grant-funded (G) sample projects in hazard level h for the given peril p
p = an index to peril (earthquake, fire, flood, wind)

4.20.3 Aggregating Results Across Perils to a Nationwide Level

One can aggregate all benefits, costs, and the BCR for all designs above (A) I-Code requirements using Equations 4-41 through 4-43.

$$B_A = \sum_p B_{A,p}$$

(Equation 4-41)

$$C_A = \sum_p C_{A,p}$$

(Equation 4-42)

$$BCR_A = \frac{B_A}{C_A}$$

(Equation 4-43)

Where,

B_A = benefit of all designs above (A) I-Code requirements and compliance with 2015 IWUIC where cost-effective
C_{2A} = cost of all designs above (A) I-Code requirements and compliance with 2015 IWUIC where cost-effective
BCR_A = BCR of all designs above (A) I-Code requirements and compliance with 2015 IWUIC where cost-effective

One can aggregate all benefits, costs, and the BCR for all federal mitigation grants using Equations 4-44 through 4-46.

$$B_G = \sum_p B_{G,p}$$

(Equation 4-44)

$$C_G = \sum_p C_{G,p}$$
(Equation 4-45)

$$BCR_G = \frac{B_G}{C_G}$$
(Equation 4-46)

Where,

B_G = benefit of all grant (*G*) funded mitigation
C_{6A} = cost of all grant (*G*) funded mitigation
BCR_{6A} = BCR of all grant (*G*) funded mitigation

4.21 Allocating Net Benefits to Stakeholder Groups

Different stakeholders bear different costs and enjoy different benefits of designing new buildings to exceed code provisions. Here is an estimate of how costs and benefits are distributed among five stakeholder groups:

1. **Developers**: Corporations that invest in and build new buildings, and usually sell the new buildings once they are completed, owning them only for months or a few years.
2. **Title holders**: People or corporations who own existing buildings, generally buying them from developers or from prior owners.
3. **Lenders**: People or corporations that lend title holders the money to buy the building. Loans are typically secured by the property, meaning that if the title holder defaults on loan payments, the lender can take ownership.
4. **Tenants**: People or corporations who occupy the building, whether they own it or not. This work uses the term “tenant” somewhat loosely, and includes visitors.
5. **Community**: People, corporations, local government, emergency service providers, and everyone else near the building or who does business with the tenants.

The project team attempted to allocate costs and benefits to various stakeholders. Developers initially bear any higher up-front construction costs, with such costs transferred entirely to subsequent building owners. While the developer would have to make a larger investment to build a more-expensive building, the developer would pass the cost on to the subsequent buyer, carrying the cost only during his or her ownership period. The added construction cost is assigned to later owners (the title holders), who transfer an estimated fraction of it to the tenants.

Building owners (the title holders) enjoy most of the benefits of reduced building repair costs, and tenants enjoy most of the reduction in content loss. The project team also examined the allocation of reduced building repair costs. If a natural disaster seriously damages a building, the title-holder might be unable to pay for the repairs and default on the mortgage, leaving the bank or other lender with a property where the resale value is less than the lender’s pre-disaster equity. The project team did not know what fraction of the reduction in property repair costs accrues to lenders; likely it is a relatively small amount, perhaps on the order of 10%. Therefore, 10% of building repairs were assigned to lenders. Since the developer will be the title holder for approximately 3 years out of the 75-year assumed life of the building, the project team assigned 3/75·90%, or 3.6% of the benefit of reduced building repair cost to the developer, 86.4% to the title holder, and 10% to the lender. Where building and content loss are calculated under one heading of property loss, the loss is approximated as two-thirds building repairs and one-third content loss.

Note, a hidden attribute of the reduction in property losses when it comes to earthquakes. Making buildings stiffer generally increases content damage rather than decreasing it. However, the increase in content damage is generally much smaller than the decrease in other aspects of property loss.

Tenants generally enjoy the benefits of reduced ALE and direct BI. The people and corporations who buy from or sell to tenants enjoy the benefits of reduced indirect BI; these people and corporations are part of the broader community.

In the case of common property insurance, such as fire or flood insurance, the title holder enjoys any reduction in insurance O&P costs (in the case of wind or fire), or reduction in administrative costs and fees (in the case of the NFIP). Since only a small fraction of properties are insured for earthquake, earthquake insurance is ignored here.

Tenants and visitors enjoy the benefits of enhanced life safety, and, to some extent, so do casualty insurers, although emergency medical care and workers' compensation insurance account for a relatively modest fraction of the acceptable statistical cost to avoid deaths and injuries. For example, the average American has far less life insurance than the U.S. government assigns to the acceptable cost to avoid a statistical fatality ($9.5 million). Only 44% of people have life insurance (LIMRA 2016). Life insurance coverage in the United States totals approximately $19.2 trillion (Life Insurance Selling Magazine 2013). Divide that by the U.S. population (321 million people in 2015) to see that the average amount of life insurance per person (including the uninsured) is just under $60,000, or about 0.6% of the $9.5 million figure. Even if the fraction is somewhat larger for non-fatal injuries, insurers probably enjoy a relatively small fraction of the life-safety benefit, on the order of 1%.

Local communities enjoy the benefits of reduced cost of urban search and rescue. The local community here are the taxpayers who support the fire department and emergency medical services.

How can the stakeholder benefits be quantified mathematically? This is represented with a matrix equation, as in Equation 4-50:

$$S = AB$$

(Equation 4-50)

Where,

> A = m x n benefit-transfer matrix, where m = number of stakeholder categories, n = number of cost and benefit categories, and entry A_{ij} is the fraction of cost or benefit

category in column j that the stakeholder in row *i* bears or enjoys. Table 2-4 presents the benefit-transfer matrix derived here.

B = *n* x 1 vector of benefit, where entry B_i denotes the cost or benefit in category *i*. A quantity in parentheses means the benefit is negative. “Negative benefit” means either an immediate cost (as in the case of construction cost) or a future cost (as in the case of future content repair cost, which generally increases rather than decreases when one builds new buildings to be stiffer).

S = *m* x 1 vector of stakeholder net benefit by stakeholder group, where entry S_i is net benefit to stakeholder group *i*

Table 4-31 contains benefit-transfer matrix A, with rows and columns labeled for clarity.

	Construction Cost	Property	ALE and Direct BI	Indirect BI	Insurance	Death, Injury, PTSD
Developer		2%			4%	
Title holder	50%	58%			86%	
Lender		7%			10%	
Tenant	50%	33%	100%			99%
Community				100%		1%

Table 4-31. Benefit-transfer matrix A.

The net benefit (the contents of vector S) means the benefit each stakeholder group experiences minus the costs they bear from designing new buildings to exceed 2015 I-Code design requirements (in the case of flood, wind, or earthquake) or to comply with the 2015 IWUIC (in the case of fire at the WUI). Some critics might object to the notion of net benefit to some stakeholder groups—especially developers—because of the implication that a positive net benefit means that a stakeholder group would or should value designing to exceed I-Code requirements. Box 4-4 addresses that question.

Policymakers regularly express interest in how any given policy option would affect employment. Although this Interim Study, like the 2005*Mitigation Saves* study, excludes job creation per se from both the benefit and the cost side of the BCR, the quantity may nonetheless interest some readers. How can job creation be quantified? The study of job creation is restricted to designing to exceed I-Code requirements for flood, wind, and earthquake, and compliance with the 2015 IWUIC for fire.

Box 4-4. Is There Really Value in Building Better?

Critics might object to the notion that owners value better buildings, based on the following observations: owners are not already constructing buildings to be stiffer or stronger; renters have not expressed a willingness to pay more for better buildings; and insurers have not recognized improved resilience in setting rates for earthquake insurance. All three statements are demonstrably false.

Would owners value better buildings? After conversations with the Building Owners and Managers Association (BOMA) of Greater Los Angeles, Lucy Jones reported (L. Jones, written communication, 20 Nov 2015),

"At my meeting with the board of the Building Owners and Managers Association of Greater Los Angeles, attendees said they would accept an unspecified greater construction cost to achieve better seismic performance, if it was mandated. They also said they would like to see it mandated because they don't want to have their building be a financial loss after the earthquake, and having the building cost more to build would just be the cost of business in Los Angeles much like higher labor costs in some areas. But even though they want the higher performance, they can't afford to pay that extra cost if they are the only ones - they don't believe that tenants will pay higher rents for seismic performance."

Which means owners would value, and even prefer, better buildings, as long as the investment does not disadvantage them relative to competitors. Some owners have already decided to pay more for better buildings, despite not being required to do so. Just two examples: for 30 years, the Cal-Tech built its new buildings 50% stronger than local code required, because it valued the better likely performance (CalTech Design and Construction 2014). A private client of Porter independently decided several years ago to design all its new dry-goods distribution centers to I_e = 1.25, exceeding the minimum strength requirement by 25% because its executives wanted better performance than the code requires. Another private client decided to build certain of its critical facilities to the same I_e factor.

What about renters' willingness to pay more for better buildings? As Davis and Porter (2016) show, a scholarly survey of 400 Californians and 400 adults from the Saint Louis, MO, and Memphis, TN, metropolitan areas shows the people generally expect and are willing to pay for better seismic performance from new buildings. The survey shows no strong effect either of household income or educational attainment.

As for insurers valuing better resilience through insurance premiums, the California Earthquake Authority (CEA) offers earthquake premium reductions for certain retrofit measures. The California State Automobile Association offered such discounts years before the formation of the CEA. Seismic vulnerability is a rating factor that affects insurance premiums, meaning that insurers support and encourage better resilience, and have done so for decades.

In any case, FEMA and this Interim Study use a broader definition of value than renters' willingness to pay. This Interim Study is concerned with value as the federal government views value, including reduced future property repair costs, future deaths and injuries, and future direct and indirect BI. Value means more than just the money that the owner saves or the tenant is willing to pay. Their value is only a portion of the value of greater resilience to society. The combination of greater strength and stiffness undeniably reduces future losses. By FEMA's own definitions, the present value of those reduced future losses is called benefit. Benefit is a value. By FEMA's definitions and procedures, building better has value.

4.22 Job Creation

Most of the marginal cost for designing to exceed I-Code requirements (at least for earthquake) comes from additional structural material: more concrete, steel, wood, and connectors. Higher open foundations for flood resistance mostly involves more material, as opposed to labor costs. Other flood measures and wind measures involve relatively more labor. However, an important focus is on jobs created by requiring more construction materials. Structural materials represent about 10% of construction cost, so an increment D in construction cost involves contractors buying about D/0.10 more structural material. Thus, a D = 0.1% increase in construction cost nationwide would involve purchasing about 10% more structural materials nationwide. It is important to relate the incremental increase in construction cost to the number of added jobs in industries that provide structural materials by supposing that the number of U.S. jobs in industries that supply structural materials scales with the quantity of domestically produced structural material.

For example, if changes in construction practice led to the United States consuming 1% more construction sand and gravel nationwide on a regular, ongoing basis, and if virtually all of U.S. consumption was satisfied by sand and gravel produced in the United States, then U.S. employment in the production of construction sand and gravel would rise by 1%, or a lesser fraction in proportion to the fraction of U.S. consumption supplied by U.S. production. If the United States employs approximately 27,000 people in the production of construction sand and gravel, and if virtually all construction sand and gravel consumed in the United States were produced domestically, then the 1% increase in demand would result in around 270 new, long-term jobs in that industry.

Some groups may contend that job creation to retrofit existing buildings (as in federal mitigation grants) would be largely short-term if it added jobs at all. The project team identified two responses: first, consider only jobs created under above-code measures, which deals with new construction. Second, even if one were to consider a retrofit, many construction firms specialize, including firms that specialize in retrofit. A long-term increase in retrofit efforts would tend to produce new employment among retrofit contractors.

Job creation for designing to exceed I-Code requirements (for earthquake, at any rate) is estimated as follows:

Step 1. List North American Industry Classification System (NAICS) classifications associated with manufacture and sale of structural materials. (See Table 4-32)

Step 2. Get recent U.S. employment data, e.g., from Bureau of Labor Statistics N = U.S. employees in manufacture and sale of structural materials.

Step 3. Estimate f = (U.S. consumption)/(U.S. production) = [(Value of Product Shipments) - (Total Export Value of Goods) - (General Import Value of Goods)] / [(Value of Product Shipments) - (General Import Value of Goods)]. (USCB 2012)

Step 4. Estimate g, increase in domestic consumption of structural materials from above-code measures. As noted above, $g = 10*D$.

Step 5. If estimating job creation at the state level, estimate h = (state construction employment)/(national construction employment), e.g., from Bureau of Labor Statistics (2017a and 2017b).

Step 6. Estimate added jobs by NAICS classification, $J \approx N*f*g = 10N*f*D$, and sum over classifications. Using values of N and f in Table 4-32, one can estimate nationwide job creation using Equation 4-51, and at a state level, using Equation 4-52.

$$J = 8{,}650{,}000*D$$
(Equation 4-51)

$$J = 8{,}650{,}000 \cdot D \cdot h$$
(Equation 4-52)

NAICS classification	*N* (1000)	*f*
Construction Sand and Gravel Mining: 212321	27.0	1.0[(c)]
Sawmills: 3211	90.7	0.78
Veneer, Plywood, and Engineered Wood Product Manufacturing: 3212	78.5	0.78
Cut Stock, Resawing Lumber, and Planing: 321912	50.1	0.78
Ready-Mix Concrete Manufacturing: 327320	95.4	1.0
Concrete Block and Brick Manufacturing: 327331	32.5[(a)]	0.99
Other Concrete Product Manufacturing: 327390	32.5[(a)]	0.97
Iron and Steel Mills and Ferroalloy Manufacturing: 331110	83.5	0.73
Rolled Steel Shape Manufacturing: 331221	55.7	0.98
Plate Work and Fabricated Structural Products 33231	159.5	0.91
Other Fabricated Wire Product Manufacturing: 332618	34.4[bc)]	0.57
Lumber, Plywood, Millwork, & Wood Panel Merchant Whsl: 423310	105.3	1.0[(d)]
Metal Service Centers and Other Metal Merchant Wholesalers: 423510	121.8	1.0[(d)]

(a) One-third of employment in a sector where data for N includes 2 others
(b) Half of employment in a sector where data for N includes 1 other
(c) Bolen, W. (2001)
(d) Assumed

Table 4-32. U.S. job-creation data for designing to exceed I-Code requirements for earthquake.

5 Project Data, Sampling, and Other Analytical Details

This chapter summarizes the data the project team acquired from federal grant programs. It also presents details of additional data acquired and of additional assumptions and procedures to deal with idiosyncrasies of project data and peril- or program-specific analysis.

5.1 Federal Mitigation Program Data

FEMA provides public-assistance funding for cost-effective hazard mitigation for eligible facilities damaged by natural disasters under Stafford Act Section 406.[18] FEMA also provides hazard mitigation funding under its HMA programs. FEMA's Federal Insurance and Mitigation Administration (FIMA) administers the HMA programs, with expenditures authorized under Stafford Act Sections 203 and 404, and the National Flood Insurance Act of 1968.[19] HMA programs include the Hazard Mitigation Grants Program (HMGP), Flood Mitigation Assistance (FMA), and Pre-Disaster Mitigation (PDM) programs, as illustrated in Figure 5-1.

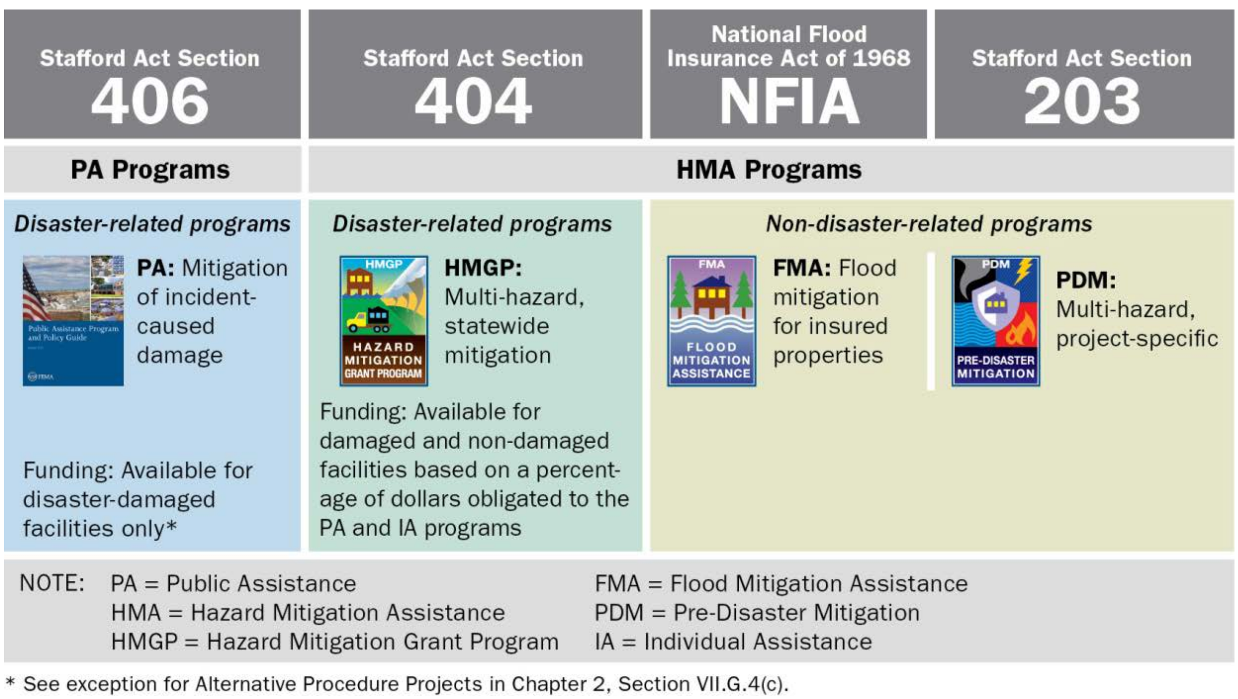


Figure 5-1. FEMA hazard mitigation programs (FEMA 2017a).

In December 2016, four federal agencies, including FEMA, provided the project team with grant data related to natural hazard mitigation for flood, wind, earthquake, and fire at the WUI. Table 5-1 lists the federal agency programs that provided grant data. Agencies tend to keep the relevant data in their own agency-specific formats; the project team merged their data into a single database with fields listed in Table 5-2. The data contained many gaps for fields that agencies do not compile or could not provide for fear of releasing personally identifiable information. Table

[18] See https://www.fema.gov/media-library/assets/documents/15271.
[19] See https://www.fema.gov/media-library/assets/documents/7277.

5-3 summarizes quantities of mitigation grants examined here. Not all of the data could be used. Some records lacked sufficiently fine geolocation information. In some cases, the project team could not determine that the record actually dealt with natural hazard mitigation. Some projects took place outside of the 48 contiguous states.

The data offer grant project amounts in grant-year dollars. The project team adjusted the totals to account for inflation using a deflator calculated as the ratio of grant-year per-capita U.S. GDP purchasing power parity (PPP), provided by the World Bank. Total project costs are shown in Table 5-4. The table reflects removing grants that could not be used or did not appear to address natural hazard mitigation, and accounts for inflation using the GDP PPP deflator. Table 5-5 presents median and mean project amounts by peril in grant-year dollars. Figure 5-2 shows the distribution of flood project amounts. Figure 5-3 shows the distribution of wind projects, Figure 5-4 earthquake projects, and Figure 5-5 flood projects.

Agency	Program
EDA	Disaster Mitigation Recovery
	Hurricane Floyd disaster 2001
	Other disasters using Floyd emergency fund 2001
	Norton Sound, Alaska 2001
	2008 Disaster Supplemental I, including Midwest Floods
	2008 Disaster Supplemental II, including Midwest Floods
	2010 Gulf Oil Spill Disaster Supplemental
	2010 Disaster Supplemental
	Federally declared disaster area
	Hurricane Katrina Disaster 2005
	Gulf Coast Disaster 2010
	Alaska Fisheries Disaster
	2012 Disaster Supplemental
	2010 Gulf Oil Spill Disaster Supplemental
	2008 Disaster Supplemental I
	2010 Disaster Supplemental
	2008 Disaster Supplemental II
	Global Climate Change Mitigation Incentive Fund
DOT	
FEMA	Flood Mitigation Assistance Grant Program (FMA)
	Hazard Mitigation Grant Program (HMGP)
	Public Assistance Program (PA)
	Pre-Disaster Mitigation Grant Program (PDM)
HUD	Community Development Block Grant Program (CDBG)

Table 5-1. Agencies and programs providing grant data.

Field	Meaning	Example
ID	*2017 Mitigation Saves* study unique integer ID	11123
DB	Program: FMA, HMGP, PDM, PA, HUD, or EDA. SBA data had no info on nat haz mitigation. DOT had too few building projects.	HMGP
DBID	*2017 Mitigation Saves* study integer ID within DB	15104
Region	FEMA region	
StateName	State name or state postal abbreviation	California
DisasterNumber	Disaster number	
DeclarationDate	Declaration date	
IncidentType	Incident type	
Peril	Peril for purposes of 2017 *Mitigation Saves study*	Earthquake
DisasterTitle	Disaster title	
ProjectNumber	Project number	DR-1008-3034-R
ProjectType	Project type	205.4: Non-Structural Retrofitting/Rehabilitating Public Structures – Seismic
ProjectTitle	Project title	Seismic Retrofit (Replacement) of Electrical Stations
ProjectDescription	Project description	
ProjectCounties	Project counties	Los Angeles
Status	Grant status	Closed
Subgrantee	FEMA subgrantee	
SubgranteeFIPSCode	Subgrantee FIPS code	
ProjectAmount	Project amount $	126524100
CostSharePercentage	Cost share percentage	58
CountyFIPS5	County FIPS5	06037
PerilOK	Peril is within *Mitigation Saves Volume 2* scope	TRUE
HazOK	County has hazard info available	TRUE
StatusOK	Project status suggests the project was actually undertaken	TRUE
WindHaz	Wind hazard level H M or L	L
WUIFireHaz	WUI fire hazard level H M or L	M
FloodHaz	Flood hazard level H M or L	L
EqkHaz	Earthquake hazard level H M or L	H

Field	Meaning	Example
StructureType	Structure type	
FoundationType	Foundation type	
PropertyPartOfProject	Property is part of project	Yes
StructureLocatedInFloodway	Structure is located in floodway	
FloodZone	Flood zone	
FloodSource	Flood source	
PostMitigationPropertyUse	Post-mitigation property use	
Latitude	Latitude decimal degrees N (truncated to 3 decimal places)	34.180
Longitude	Longitude decimal degrees E (truncated to 3 decimal places)	-118.445
FirstFloorElevation	First floor elevation ft	
YearBuilt	Year built	
StreetName	Street name	AETNA STREET
City	City name	VAN NUYS
ZIP	ZIP code	91401

Table 5-2. Integrated Project database format.

Agency	Program	Project dates	Peril	Projects	Properties	Amount ($M)
EDA	Various	2000-2016	Flood	159		$ 800
			Wind	67		$ 200
FEMA	FMA	1993-2016	Flood	1,063	2,873	$ 789
	HMGP	1993-2016	Earthquake	558	3,986	$ 2,470
			Fire	23	108	$ 22
			Flood	4,355	30,288	$ 7,022
			Wind	3,816	20,446	$ 3,061
			HMGP subtotal		54,828	$ 12,575
	PA	2001-2016	Earthquake	457		$ 29
			Fire	83		$ 3
			Flood	9,672		$ 168
			Wind	13,613		$ 5,534
			PA subtotal	23,825		$ 5,734
	PDM	1993-2016	Earthquake	87	424	$ 286
			Fire	13	392	$ 15
			Flood	239	1,345	$ 441
			Wind	175	205	$ 171
			PDM subtotal		2,366	$ 913
			FEMA total		60,067	$ 20,011
HUD	CDBG	2001-2015	Flood	99		$ 92

Table 5-3. Summary of grant data, in grant-year dollars.

Peril	Cost (billions)
Riverine flood	$ 11.50
Wind	$ 13.60
Earthquake	$ 2.20
Fire at WUI	$ 0.06
Subtotal, grants	***$ 27.4***

Table 5-4. Total project costs in billions.

Peril	Median	Mean
Flood	$ 33,000	$ 640,000
Wind	$ 23,000	$ 990,000
Earthquake	$ 168,000	$ 1,700,000
Fire	$ 39,000	$ 380,000

Table 5-5. Median and mean project amounts in project-year dollars.

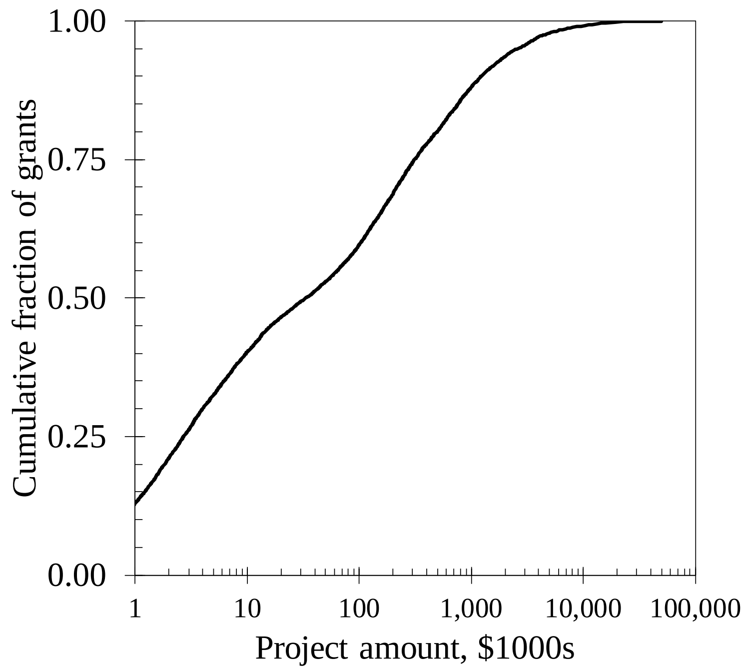


Figure 5-2. Flood project amounts in thousands of grant-year dollars.

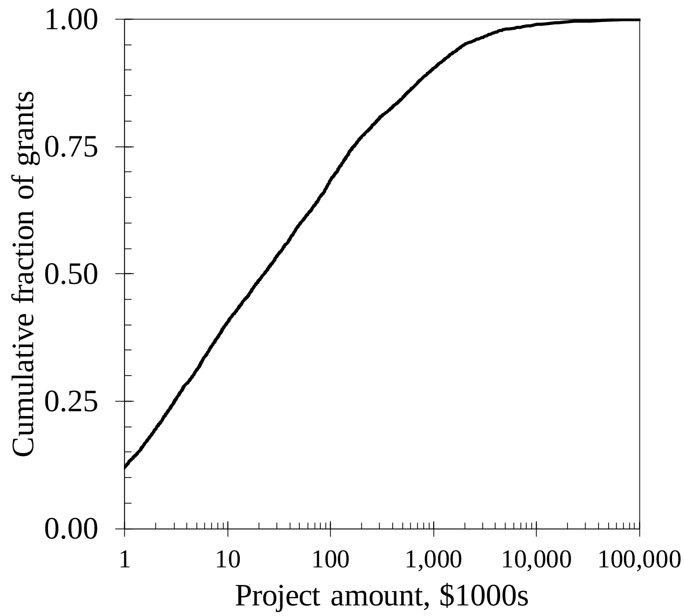


Figure 5-3. Wind project amounts in thousands of grant-year dollars.

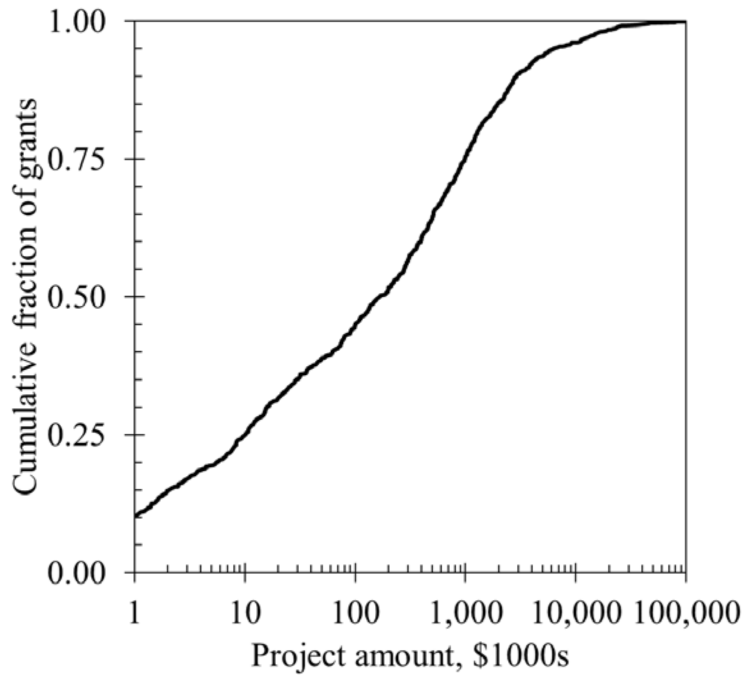


Figure 5-4. Earthquake project amounts in thousands of grant-year dollars.

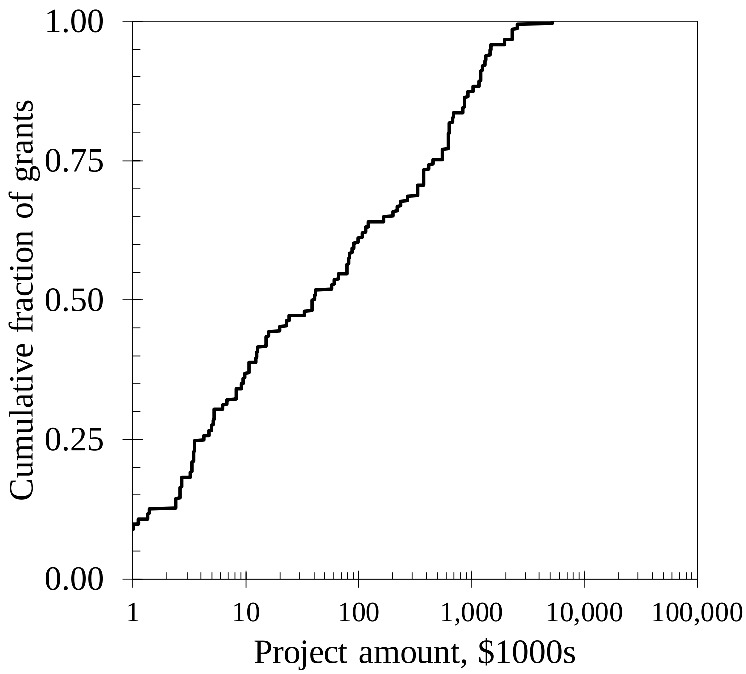


Figure 5-5. Fire project amounts in thousands of grant-year dollars.

5.2 Designing to Exceed I-Code Requirements for Riverine Flood

5.2.1 Building Inventory for Above-Code Design for Riverine Flood

Hazus Release 3.2 represents building exposure in both aggregate and site-specific form. The aggregated building inventory, referred to as GBS, is reported at the level of 2010 census blocks while the UDF is reported as points. One improvement in Hazus pertains to the way that it represents buildings in the GBS. A fundamental assumption of the GBS is that all buildings are evenly distributed within a given census block. In the version of Hazus available at the time of the 2005 *Mitigation Saves* study, census blocks were clipped to remove water bodies. However, they still often overlapped areas where buildings were unlikely to be constructed such as locations that were predominantly forested or vacant.

The current release of the Hazus flood model applies a dasymetric adjustment methodology that has been used to refine census block boundaries by removing these areas. Figure 5-6 illustrates an area that has been overlain with dasymetrically modified 2010 census block boundaries. Note that large portions of this image contain forested land with no structures. While these boundaries do not necessarily reflect a precise depiction of where structures do and do not exist in every community, they generally provide a more realistic representation of building locations within a community than did the boundaries used in earlier Hazus flood model releases, including the one used in the 2005 *Mitigation Saves* study.

Figure 5-6. Example of dasymetrically adjusted census block polygons.

UDF inventory is developed from user-supplied information that describes the structural design and occupancy characteristics of individual buildings. It is not intended to provide a detailed assessment of mitigation impacts on a single structure, but when viewed as a portfolio of building points—as is the case with this Interim Study—it offers a much more refined assessment of the impact of mitigation than is otherwise possible. UDF-based outputs include estimates for building damage percent and dollar loss; content damage percent and dollar loss; and inventory dollar loss. All structure categories that are represented in the GBS can also be modeled as part of the UDF inventory. Ideally, UDF structures are located at the centroid or even the lowest adjacent grade of a structure. However, that type of inventory can only be created if suitable data resources are available.

In the analysis of above-code design requirements pertaining to riverine floods, the project team used a combination of the Hazus UDF inventory and the Hazus GBS Inventory. The tools developed to generate the UDF inventory placed the locations at the centroid of parcels. Figure 5-7 provides a hypothetical example of UDF inventory.

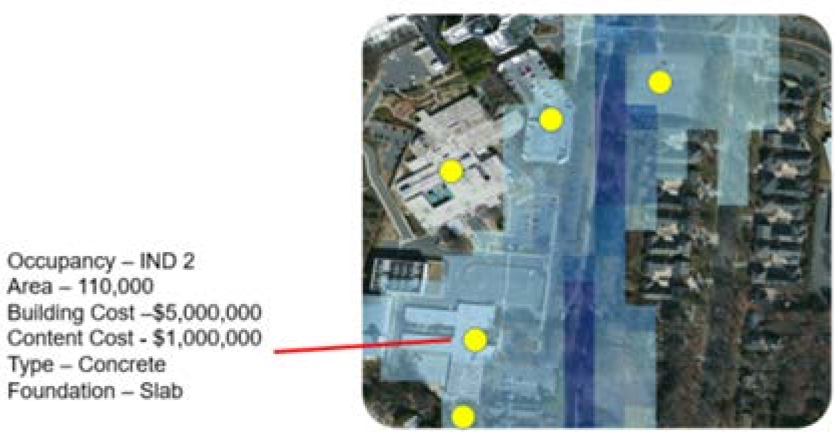


Figure 5-7. Example of UDF inventory.

5.2.2 Cost of Designing to Exceed I-Code Requirements for Riverine Flood

The project team calculated the cost to build new single-family dwellings at multiple elevations at and above I-Code requirement using CostWorks' U.S. national averages reported in RSMeans construction cost estimates as of February 2017. The project team estimated costs accounting for the following:

- Different types of foundation were addressed: concrete masonry unit walls and piers, poured concrete walls and piers, concrete masonry unit piers, stemwall, and fill.
- Cost calculation took into account material cost, equipment, and labor required for the construction of a one-foot addition to a foundation during the construction process consisting of concrete masonry units (186 SF).
- Costs were calculated for four types of building sizes (1,500 and 3,000 square feet with foundation size 30 feet by 50 feet, also 2,400 and 4,800 square feet with foundation size 40 feet by 60 feet). Pier spacing was calculated using common lumber framing sizes and joist lengths.
- The project team included the cost of compliance with the ADA: ramps with a 1:12 slope and appropriate allowances for landings.
- Final cost estimates were summarized by closed and open foundation calculations as well as building types (8 types of estimates are provided). These were added to the building replacement value to estimate the total cost of constructing a new structure with X foundation height.
- Cost estimates were multiplied by a locational factor to account for regional difference.

Table 5-6 lists the cost estimates used for the 8 variations of building size and foundation types that were generated using the above listed information. The figures include compliance with additional features required by the ADA. These costs may seem low. However, that it is usually far less expensive to build better initially than to retrofit existing buildings to the same level of resistance.

	Estimated national cost to build to higher elevation, per house					Adjustment factor	
Code	**BFE + 1**	**BFE + 2**	**BFE + 3**	**BFE + 4**	**BFE + 5**	**Georgia**	**Indiana**
A	$ 883	$ 1,766	$ 2,688	$ 3,571	$ 4,493	0.81	0.93
B	$ 1,636	$ 3,271	$ 4,907	$ 6,542	$ 8,332	0.81	0.93
C	$ 883	$ 2,159	$ 2,727	$ 3,610	$ 4,532	0.81	0.93
D	$ 1,636	$ 3,271	$ 4,907	$ 6,542	$ 8,332	0.81	0.93
E	$ 1,203	$ 2,405	$ 3,663	$ 4,866	$ 6,124	0.81	0.93
F	$ 2,168	$ 4,336	$ 6,505	$ 8,673	$11,048	0.81	0.93
G	$ 1,203	$ 2,461	$ 3,719	$ 4,921	$ 6,179	0.81	0.93
H	$ 2,168	$ 4,336	$ 6,505	$ 8,673	$11,048	0.81	0.93

Table 5-6. Estimated costs to build new buildings higher to reduce risk from riverine flood.

5.2.3 Life-Safety and Additional Living Expense Benefits of Designing to Exceed I-Code Requirements for Riverine Flood

To estimate benefits of designing to exceed I-Code requirements in terms of reduced deaths, injuries, PTSD, and ALE, the project team took the reduction in loss as proportional to the reduction in building and content losses for single-family dwellings (RES1). See Section 5.3.3 for some additional analytical details common to above-code design and mitigation grants.

5.3 Grants for Riverine Flood Mitigation

5.3.1 Building Inventory for Flood Mitigation Grants

For the analysis of public-sector grants, the Interim Study applied two types of Hazus inventory for the analysis: UDF and GBS. The following guidelines were applied to develop a Hazus-compliant GBS and UDF building inventory from information contained in the grant database.

Occupancy. The StructureType field in the grants database contained information on structure use. Hazus occupancy classes are mapped as shown in Table 5-7.

Structure type	Hazus occupancy
2-4 family	RES3A (duplex). Note that Hazus breaks 2-4 units into two classifications, RES3A and RES3B. It was not possible to differentiate which is correct from the data in the database, therefore RES3A is used.
Manufactured home	RES2 (manufactured housing)
Single family	RES1 (single-family dwelling)
Blank	RES1 (single-family dwelling), the most common type in the database

Table 5-7. Mapping from grants database to Hazus occupancy classes for riverine flood.

Location. The project team used both the GBS and the UDF inventories in the completion of public-sector grant analysis. Thus, each inventory type had to be modified based on the information provided in the grant record to reflect the location as well as associated attributes for each acquired building.

The grant database contained multiple records and coordinates for a single grant. The project team assumed that each record represented a single building in the grant. Locations of user-defined facilities, which were used in the calculation of building and content losses for acquired structures, were located at the coordinates specified in the grant database where possible. However, in a few instances it was necessary to move one or more of these building points. In such instances, the new location was made to be as close to the original location as possible.

The final building location for each acquired building was based on three criteria. First, it had to be within the 100-year depth grid inundation area generated by Hazus, since it was assumed that the structure may not have been acquired due to flooding at lesser return periods. Second, it had to be located within one of the dasymetric census block boundaries. This was necessary to allow for the calculation of losses that had to be derived from the GBS inventory which only applied to these boundaries. Finally, it had to be in a location where the depth of water to which the structure was exposed exceeded the building first floor elevation for the 100-year return period.

Cost. The Indiana State Hazard Mitigation Officer told the project team that for the 31 FEMA grants for demolition and acquisition of Indiana buildings between 2007 and 2017, communities spent \$21 million of \$32 million (67.8%) awarded. When reviewed individually, this percentage was consistent across most of the individual projects. Only two small outliers had higher percentages. The project team was torn about whether to apply this fraction across the board, just to Indiana grants, or not at all. The project team lacked the resources to check with other state hazard mitigation officers. FEMA staff had assured the project team that the project amounts in the database were their best estimates of actual project costs. To assume that all other grants were similarly less costly than the grant database indicated would tend to reduce costs and increase BCRs. To apply the fraction to just the Indiana grants would add a degree of inconsistency and would also increase the BCR. The project team selected the most conservative of the three options and used the grant amount in the FEMA database to estimate BCRs.

Building count. The grant database provided a count of buildings that were categorized as Hazus occupancies RES1, RES2 or RES3A. Using this information, the project team created a UDF inventory representing acquired structures. The project team also updated the GBS building counts for each census block in which an acquisition occurred.

Square footage. The grant database did not contain building square footage, but Hazus requires this value for the calculation of selected types of losses. The project team used the Hazus occupancy classes and applied the average building areas assumed by Hazus Release 3.2, as shown in Table 5-8.

Using the calculated buildings areas, the project team updated both the UDF inventory and the GBS. Values applied to UDF were building-specific, based on the criteria above. Values applied to the GBS were cumulative based on the quantity of each type of structure. For example, if a grant included 2 RES1 buildings in the same census block, the project team adjusted the building square footage for that census block in the pre-mitigation analysis to add 3,600 square feet to the RES1 square footage table (e.g., 2 x 1,800 square feet).

Building replacement cost. Hazus requires a building replacement cost to calculate flood losses. However, project amounts in the grant database were based on pre-damaged appraised value. They do not reflect the replacement cost of buildings acquired. For this reason, the project team applied a methodology similar to that used to develop the default Hazus inventory. In that methodology, default replacement costs are based on building square footage multiplied by RSMeans construction values and then further adjusted to reflect regional variations. Table 5-9 shows how the project team estimated building replacement costs. The project team assumed uniform replacement costs within an occupancy class. For example, if total RES1 building replacement cost was estimated to be $1 million for 10 single-family dwellings (RES1), each was taken to have a replacement cost of $100,000. Table 5-11 shows Hazus' assumed square-foot costs.

Occupancy	Square footage
RES1	1,800
RES2	1,475
RES3A	2,200
RES3B	4,400
RES3C	8,000
RES3D	15,000
RES3E	40,000
RES3F	80,000
RES4	135,000
RES5	25,000
RES6	25,000
COM1	110,000
COM2	30,000
COM3	10,000
COM4	80,000
COM5	4,100
COM6	55,000
COM7	7,000
COM8	5,000
COM9	12,000
COM10	145,000
IND1	30,000
IND2	30,00
IND3	45,000
IND4	45,000
IND5	45,000
IND6	30,000
AGR1	30,000
REL1	17,000
GOV1	11,000
GOV2	11,000
EDU1	130,000
EDU2	50,000

Table 5-8. Hazus estimates of average building area.

Structure type	Method
2-4 Family (RES3A)	1. Multiply the total square footage in the acquisition by $113.39. 2. Multiple the value in Step 1 by the Hazus regional adjustment factor for the county
Manufactured home (RES2)	1. Multiply the total square footage in the acquisition by $41.97. 2. Multiply the value in Step 1 by the Hazus regional adjustment factor for the county
Single family (RES1)	1. Multiply the total square footage in the acquisition by $115.20 (Average 1 story average base cost). 2. If the value in the FoundationType field of the grant database is 'Basement' multiply the total square footage by $30.80 (Finished Basement cost). Add this sum to the total from Step 1. 3. Multiply the value in Step 2 by the Hazus regional adjustment factor for the county in which the acquisition occurs. *Note: The grant database does not specify the condition, number of stories, or basements, so it was assumed that RES1 structures were in average condition and that that they were 1 story with finished basements.*

Table 5-9. Calculating building replacement cost for public-sector riverine flood mitigation.

Content replacement cost. Content losses matter. However, the grant database does not include content values. The project team estimated the content replacement cost of RES1, RES2 and RES3A buildings as half the building replacement cost, consistent with Hazus' methodology for estimating content values. Content replacement costs were allocated equally among buildings of the same occupancy class.

Foundation type, first-floor elevation, and NFIP date of entry. The project team applied default values from Hazus Release 3.2 for general-building-stock foundation type, first-floor elevation, and NFIP date of entry for the following reasons:

- Foundation type was not populated for many of the grants.
- The grant database did not include information on the date that communities in which acquired structures were located achieved NFIP compliance.
- The field for first floor elevation was sparsely populated in the grant database. In many cases it was reported relative to sea level, not the above-ground height. In addition, there was no way to populate structure specific first floor elevation values in the Hazus GBS inventory.

Occupancy	Hazus Definition	Occupancy Example	RSMeans Cost
RES1	Single-Family Dwelling	Refer to hzRES1ReplCost	
RES2	Manufactured Housing	Manufactured Housing	41.97
RES3A	Multi-Family Dwelling – small	Duplex	113.69
RES3B	Multi-Family Dwelling – small	Triplex/Quads	99.95
RES3C	Multi-Family Dwelling – medium	5-9 units	179.48
RES3D	Multi-Family Dwelling – medium	10-19 units	168.80
RES3E	Multi-Family Dwelling – large	20-49 units	184.58
RES3F	Multi-Family Dwelling – large	50+ units	173.83
RES4	Temporary Lodging	Hotel, medium	189.42
RES5	Institutional Dormitory	Dorm, medium	203.86
RES6	Nursing Home	Nursing home	207.02
COM1	Retail Trade	Dept Store, 1 st	109.60
COM2	Wholesale Trade	Warehouse, medium	106.43
COM3	Personal and Repair Services	Garage, Repair	129.25
COM4	Professional/Technical/Business Service	Office, medium	175.24
COM5	Banks	Bank	253.94
COM6	Hospital	Hospital, medium	335.67
COM7	Medical Office/Clinic	Med. Office, medium	241.31
COM8	Entertainment & Recreation	Restaurant	223.98
COM9	Theaters	Movie Theatre	167.98
COM10	Parking	Parking garage	76.21
IND1	Heavy	Factory, small	130.37
IND2	Light	Warehouse, medium	106.43
IND3	Food/Drugs/Chemicals	College Laboratory	206.74
IND4	Metals/Minerals Processing	College Laboratory	206.74
IND5	High Technology	College Laboratory	206.74
IND6	Construction	Warehouse, medium	106.43
REL1	Church	Church	179.35
AGR1	Agriculture	Warehouse, medium	106.43
GOV1	General Services	Town Hall, small	137.50
GOV2	Emergency Response	Police Station	233.80
EDU1	Schools/Libraries	High School	173.88
EDU2	Colleges/Universities	College Classroom	193.62

Table 5-10. Hazus square-foot replacement costs.

Other details of UDF parameters. A few additional assumptions were required to employ a user-defined-facility inventory:

- A separate UDF database containing individual records for each building was developed for each grant.
- Building-specific occupancy type, replacement cost, square footage, and content cost for each UDF point were derived from the procedures described above.

- The grant database did not report Hazus building type—the material from which structures are constructed. This value must be reported in the UDF inventory. Therefore, RES1, RES2 and RES3A structures were assumed to be constructed with wood.
- The grant database did not report the number of stories for acquired structures. Therefore, RES1, RES2 and RES3A structures were all assumed to be 1 story.
- Missing first floor elevations in the grant database, or first floor elevations reported with respect to sea level as opposed to number of feet above grade, were populated with the pre-FIRM Hazus default for the foundation type specified in the grant database. In other words, it was assumed that these structures had not been elevated as a mitigation measure prior to acquisition. For example, a RES1 building with a foundation type of crawl space received a first-floor elevation value of 3 feet.
- If year built was not provided in the grant database, it was assumed to be 1900. Note that this value is *not* used to determine losses for UDF.
- In a few instances, the latitude and longitude coordinates in the grant database were missing or incomplete (such as instances in which no decimal places were provided). In these situations, the project team estimated location based on street address, if populated. If no street address was available, the point for the building was placed in close proximity to the majority of the other structures acquired under the grant.

5.3.2 Riverine Flood Grant Sample

Grants were selected for inclusion in this Interim Study based on the following criteria:

- Must be either a demolition or acquisition project
- Must specify coordinate values for structures acquired by the grant
- Must specify the project amount
- Must only include demolition or acquisition of single family, manufactured home, or 2-4 family structures.

Grants from only two programs (HMPG and PDM) met these criteria. These programs represent the majority of flood project dollar amounts. Figure 5-8 shows the location of the counties in the sample. Table 5-11 presents the number of single-family dwellings (Hazus RES1 occupancy), manufactured homes (RES2) and 2-4-family homes (RES3A) acquired by each sampled grant.

Figure 5-8. Locations of grants selected for the analysis of the effectiveness of flood-prone structure acquisitions.

Program	County	Single-family dwellings	Manufactured homes	2-4-family homes
HMPG	Morgan, IN	30	0	0
HMPG	Wagoner, OK	13	0	0
HMPG	Decatur, GA	2	0	0
PDM	DeKalb, GA	8	0	0
HMPG	Polk, WI	1	8	0

Table 5-11. Distribution of occupancies within sampled flood grants.

5.3.3 BCA of Riverine Flood Grants

Building and content losses. The project team calculated post-mitigation building and content losses using the default Hazus GBS for each of five mean recurrence intervals: 10 (10% annual chance), 25 (4% annual chance), 50 (2% annual chance), 100 (1% annual chance), and 500 (0.2% annual chance) years. For each Hazus occupancy type represented in the grant, the project team summed building and content losses over the relevant census blocks. The team limited the census blocks for which values were recorded to those in which acquired structures were located prior to the acquisition.

To calculate pre-mitigation conditions, the Interim Study applied a combination of Hazus GBS inventory and Hazus UDF inventory. The UDF inventory was updated to represent the pre-mitigation location and conditions of the structures acquired by each grant. For each grant, the Hazus study region for the first scenario was duplicated to ensure that the same hazard was applied for pre- and post-mitigation. The UDF inventory representing the buildings acquired through the grant was then imported into the duplicated region and the GBS inventory was modified to reflect the mitigated buildings addressed by the grant. Tables specifically modified included those reporting square footage, building count, dollar exposure, and content exposure.

Direct BI losses. Hazus analysis was performed for the default GBS in order to estimate post-mitigation conditions for BI losses. The project team calculated and reported BI across all Hazus occupancy types. Hazus calculated BI components included income loss, rental income loss, wage loss, and direct loss. These were summed by full replacement value for the census blocks included in the Interim Study and recorded for calculating the BCR. Census blocks for which values were recorded included only those in which acquired structures were located prior to the acquisition. This step was repeated for each mean recurrence interval: 10 (10% annual chance), 25 (4% annual chance), 50 (2% annual chance), 100 (1% annual chance), and 500 (0.2% annual chance) years.

To estimate direct and indirect BI loss, the same methodology for post-mitigation analysis was applied to pre-mitigation analysis. This means that the losses were drawn exclusively from the Hazus GBS analysis for both pre- and post-mitigation assessment. To address an error in the calculation of direct economic loss discovered in recent testing of Hazus Release 3.2, the project team multiplied Hazus' income loss, rental income loss, wage loss, and direct loss values by 100.

Deaths, injuries, PTSD, and sheltering. To calculate post-mitigation cost of injuries, deaths, and relocation, the project team mapped the Hazus GBS by building count for each occupancy class in the grant. Next, for each census block with an acquired building, the project team visually estimated the percentage of the block that was inundated by the 1% annual chance flood. The project team multiplied that percentage by the total number of buildings for each specific occupancy. For example, if there were 10 single-family dwellings (RES1) in the census block and an estimated 70% of the census block was inundated by the 1% annual chance flood, then 7 RES1 buildings were assumed to be inundated. The project team based this approach on the Hazus assumption that buildings are evenly distributed within a census block. This Interim Study used the dasymetrically adjusted census blocks in Hazus Release 3.2, which have been modified to remove unpopulated areas such as vacant land, forests, water bodies, etc. The resulting census-block boundaries generally cover only populated areas. Thus, the assumption of even distribution of buildings, while not representative of every community, is relatively reasonable.

To calculate instance of death, nonfatal injury, and PTSD, the project team estimated the number of occupants and the number of impacted households as shown in Table 5-12. The project team estimated instances of injuries and PTSD as shown in Equations (5-10) through (5-4). In the equations, H denotes number of inundated households, P the total population that experiences at least some flooding, and N_1, N_2, N_4, and N_{PTSD} denote the number of instances of Hazus level-1 injury, Hazus level-2 injury, death, and PTSD, respectively. The project team estimates that essentially no Hazus level-3 injuries result from flooding.

To calculate ALE, the project team assumed each household that experiences flooding is out of its home for 360 days. The project team calculated these losses only for flooding with mean recurrence intervals in excess of 25 years. To determine the pre-mitigation costs related to injuries, deaths, PTSD, and ALE, the project team assumed that all of the acquired structures were in the inundation area and added the number of acquired structures to the number of structures assumed to contribute to social loss in post-mitigation analysis. Acceptable costs to avoid future statistical injuries, deaths, and instances of PTSD are the same as used elsewhere in this Interim Study. Likewise, the costs per day of ALE used here are the same as elsewhere in this Interim Study.

Occupancy	Description	Occupants	Households
RES1	Single-family dwelling	Building count x 2.5	Building count
RES2	Manufactured housing	Building count x 2.5	Building count
RES3A	Duplex	Building count x 5	Building count ÷ 2

Table 5-12. Estimated number of occupants per building for use in estimating benefits of grants to mitigate riverine flooding.

$$N_1 = 0.1275 \cdot H$$
(Equation 5-1)

$$N_2 = 0.04 \cdot H$$
(Equation 5-2)

$$N_4 = 0.0008 \cdot H$$
(Equation 5-3)

$$N_{PTSD} = 0.15 \cdot P$$
(Equation 5-4)

5.4 Designing to Exceed I-Code Requirements for Hurricane Surge

A common approach to increase the elevation of a coastal dwelling is to raise the building on wooden piles. The project team used construction cost estimates that appear in Appendix E of FEMA P-550 (2009d). Costs were developed in 2006 for the First Edition of FEMA 550 and provide rough order-of-magnitude estimates for both labor and material for three scenarios: elevated 0 to 5 feet above grade, elevated 6 to 10 feet above grade, and elevated 11 to 15 feet above grade. These costs were updated to 2017 prices using the Consumer Price Index (CPI) Inflation Calculator and returned estimates of approximately $1,150 per foot of elevation. Wooden stairs add approximately $300 per foot of elevation (RSMeans C2010 110 1150), for a total of approximately $1450 per foot of elevation. Some houses have wheelchair ramps. How many, and at what cost? Examination of 682 sample houses in 5 coastal cities listed in vrbo.com suggests that approximately 5% are wheelchair accessible. (Miami FL: 6 of 101 are wheelchair accessible = 6%; Biloxi MS: 6 of 26 = 23%; Galveston TX: 18 of 459: 4%; Charleston SC: 1 of 54 = 2%; Tampa FL 5 of 42: 12%; total 36 of 682 = 5%).

These data imply that on the order of 5% of new homes with greater elevation would also have wheelchair ramps. The 5% figure coincidentally agrees with HUD requirements that 5% of federally funded new homes in developments must comply with requirements of the ADA, and must therefore have wheelchair ramps. Realistically, the figure could rise in coming decades as the American population ages. An informal survey of online estimates of the cost of permanent wheelchair ramps suggests costs range widely, from $1,000 to $3,000 per foot of elevation. (Sources: NCSU 2004, Networx 2011, ProMatcher 2017, Angies List 2013. The project team adds 0.05 × $2000 = $100 per foot of elevation for wheelchair ramps, accounting for the fact that only some new houses will be built with wheelchair ramps. With nominal additional costs for utility risers and additional exterior closure material for ground-level storage space, the total cost is therefore approximately $1,550 per foot of elevation.

5.5 Grants for Wind Mitigation

Stratified sampling of mitigation projects by hazard level yielded a total of 48 projects: 19 low-hazard, 14 medium-hazard, and 15 high-hazard. The project team could not use several of the records selected at random for sampling, typically for the following reasons:

1. **Insufficient data.** The database did not contain enough information to determine exactly what mitigation had taken place, and the project team could not find sufficient supplementary information from the internet or the state hazard mitigation officer.
2. **Not actually mitigation**. Many grants that appeared at first glance to be about mitigation turned out in fact to reflect mostly or entirely post-event rebuilding.
3. **Not about mitigating buildings.** The mitigation was part of a distributed utility or transportation lifelines such as electrical power or roads, whereas the present project focuses on buildings. (A future area of study under this project will address utility and transportation lifelines.)
4. **Public services.** The mitigated properties were essential facilities such as hospitals or fire stations, where quantifying life savings outside of the mitigated facility was beyond the scope of this project.

To select 15 valid samples by hazard level required several iterations of sampling. After the initial sampling, several projects appeared to have very high or very low BCRs. The mitigation of two vulnerable buildings that house high-value equipment resulted in BCRs exceeding 50. Two community restrooms in recreation areas that were also intended to serve as tornado shelters did not appear well suited for use solely as tornado shelters. Perhaps they had been hardened because visitors would have no other viable alternative in the event of a tornado. Their BCRs approached zero. But this is speculation. The project team could not determine details of these projects sufficiently to be confident of the estimated BCR, so the project team excluded these results. Ultimately the project team analyzed fewer than its intended 15 projects per hazard level. Of the mitigation efforts selected, 14 addressed hurricane hazards and 34 dealt with tornadoes. There were few building mitigation projects in medium- and low-hazard regions. The low- and medium-hazard projects primarily protected life safety with tornado safe rooms and shelters. There were no hurricane projects selected in low-hazard locations.

5.6 Designing to Exceed I-Code Requirements for Earthquake

5.6.1 Cost to Build New Buildings to Exceed I-Code Requirements for Earthquake

This section largely quotes Porter (2016a). There are several reasons why designing to exceed 2015 I-Code requirements for earthquake, as conceived here, may not drastically increase construction costs. Informal discussions with four California engineers suggest that designing to $I_e = 1.5$ would increase construction costs on the order of 1 to 3 percent (D. Bonneville, verbal communication, Jan 2015; E. Reis, verbal communication, Apr 2014; J. Harris, verbal communication, Aug 2015; R. Mayes, verbal communication, Jan 2015). A fifth source is given by NIST GCR 14-917-26 (NEHRP Consultants Joint Venture, 2013), in which the authors found that redesigning six particular buildings in Memphis, TN, to comply with the 2012 IBC rather than the 1999 Southern Building Code, would increase their strength on average by 60%, and would increase their construction cost between 0.0 and 1.0%.

A sixth source of support can be found in Olshansky et al. (1998), who estimated a similar marginal cost to increase from no seismic design to code minimum. It is further supported by the estimated cost to achieve an immediate occupancy performance level rather than life safety for one of the index buildings of the CUREE-Caltech Woodframe Project (Porter et al. 2006). In California, the marginal construction cost increase of 1–3% would translate to a much smaller marginal development cost increase, since land can constitute more than half the value of a building, and land value is unaffected by I_e.

An eighth argument can be seen in the fact that costs do not differ dramatically between locations with dramatically different design strengths. One could build five architecturally identical buildings in (A) Sacramento, California, (B) San Diego, California, (C) eastern San Francisco, and (D) western San Francisco, and find that they have site-class-adjusted, short-period, risk-targeted maximum considered earthquake shaking values (denoted S_{MS} in ASCE/SEI 7-10) of 0.8g, 1.2g, 1.5g, and 2.3g, respectively. Pluck the life-safe building at (D) out of the ground and place it 10 km east at (C) and it will satisfy design for I_e = 1.5. Place it 800 km south at (B) and it would nearly satisfy I_e = 2.0, or a mere 140 km northeast at (A) to satisfy I_e = 3.0. If it were unaffordable to build buildings 50% stronger than life safety, there would be no new construction in San Francisco, and all new development would take place 140 km away in Sacramento.

Some people might not believe such low marginal costs are realistic. How can such a strength increase not produce a similar cost increase? Consult a square-foot cost manual such as RSMeans (2015) and one will find that approximately 67% of construction cost of a new office building is spent on the architectural, mechanical, electrical, and plumbing elements (Figure 5-9), approximately 17% on O&P, and of the remaining 16% structural cost, approximately half is spent on labor. Most of the final 8% (mostly structural material) is spent on the gravity-resisting system: the foundation, floor slabs, and gravity-resisting columns and beams. Of the small remaining portion that is spent on materials for the earthquake load-resisting system (perhaps as much as 2%), consider that strength does not increase linearly with quantity of material, but can increase with the square or a higher power of material. For example, a W44x230 wide-flange steel shape is about 63% stronger than a W30x191 shape but weighs (and therefore costs) only about 20% more. In that particular case, strength increases with cost to the power of 2.6 (e.g., $1.2^{2.6}$ = 1.63). More-extreme cases can be cited.

In light of these observations, it seems reasonable to estimate that I_e = 1.5 produces a 1% increase in construction cost, on average, overall, and that other values increase cost in proportion. The project team does not assert that the cost of every building increases in such a simple, linear way. Some increments of design strength for some buildings would require changes in foundation design that could dramatically increase construction cost. On the other hand, some buildings might increase in construction cost at a lower rate relative to I_e because of their inherent strength. As with other aspects of this Interim Study, these costs are estimated overall averages, not uniform truths that apply to every single building.

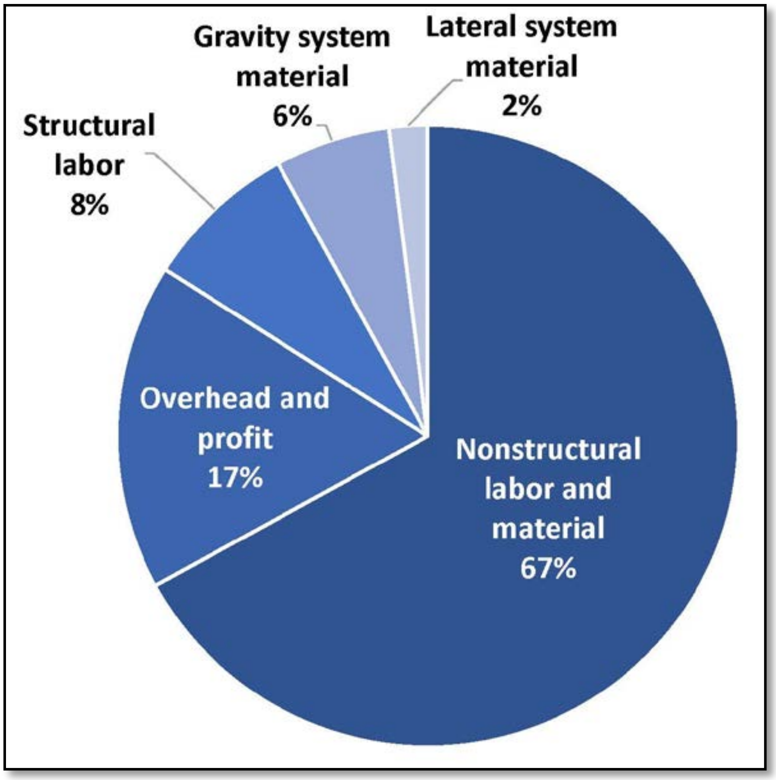


Figure 5-9. Proportional cost of new office building construction and impact on construction costs associated with increasing lateral strength.

5.6.2 Vulnerability of Buildings that Exceed I-Code Requirements for Earthquake

Hazus does not offer tabulated vulnerability functions for buildings, but rather creates them as needed for internal use only. They cannot be used outside of Hazus, which means they cannot be used in conjunction with modern seismic hazard information. Because the project team committed to using modern seismic hazard information, using Hazus directly (or the Hazus Advanced Engineering Building Module or FEMA BCA Tool) is not an option for evaluating seismic risk to buildings in the present project.

Furthermore, Hazus' seismic vulnerability functions reflect a single value of strength and stiffness for each of its four code levels and each of three special design levels. These are generally consistent with design of the 1990s, when Hazus was developed and prior to the advent of design for site-specific seismic hazard (albeit inconsistent even with then-current near-fault design modifiers in the final UBC). Since the 2000 and 2003 editions of the IBC, engineers have designed buildings with minimum lateral strength that varies from location to location—even a few kilometers can make a 50% difference in design strength, and a 2-times difference over distances as small as 150 km. Thus, to use a single vulnerability function for a particular high-code model building type can introduce gross—and unnecessary—errors in building capacity and therefore risk. This is unnecessary because it is practical to create seismic vulnerability functions that are consistent with modern design, considering design for site-specific seismic hazard.

How can one create the required vulnerability functions for classes of buildings that exceed 2015 I-Code requirements? For reasons discussed in Chapter 4, FEMA P-58 would be ideal for individual buildings, and FEMA P-58 in combination with the Global Earthquake Model's (GEM) analytical methodology (FEMA 2012d; Porter et al. 2014) would be ideal for building classes. They can handle structural and nonstructural damage, repair costs, life-safety impacts, and repair time. These tools have not yet been automated to the point where they can practically address the approximately 700,000 combinations of lateral force resisting system (28 non-obsolete model building types), height range (3 ranges), occupancy class (28 occupancy classes), MCE_R shaking (31 levels), and degree of extra strength and stiffness (10 I_e levels), required for the present analysis.

Porter (2009a, b) offers a more approximate but readily automated method to create tabular vulnerability functions entirely consistent with Hazus. By changing particular model parameters (especially the seismic response coefficient C_s of ASCE/SEI 7), one can create vulnerability functions that are consistent with designing for site-specific seismic hazard both for code-level and for designing to exceed I-Code requirements. For example, one can reflect the vulnerability differently of buildings in which design strength C_s = 0.4g in northwestern Tennessee than similar buildings in which C_s = 0.3g in western San Francisco, C_s = 0.2g in eastern San Francisco, C_s = 0.13g in San Diego or Sacramento, etc. One can reflect the vulnerability of designing to exceed I-Code requirements with a 1.5 seismic importance factor for a location with code-level C_s = 0.2g using, for example, a vulnerability function for C_s = 0.3g. The greater stiffness required for designing to exceed I-Code requirements can be similarly reflected through a smaller value of elastic period T_e.

Advantages and disadvantages of the three approaches are summarized in Table 4-13. The project team selected option 2. See Appendix K for details of the analytical methodology. See Box 4-2 for more discussion.

Option	Pros	Cons
1. Porter (2009a,b) high-code vulnerability functions	Simple; already published	Inconsistent with design for site-specific seismic hazard since at least 2000, e.g., ASCE 7-10 S_{DS} and S_{D1}, & therefore likely grossly inaccurate. Uses 1990s-era pushover approximations of structural response.
2. Create new high-code vulnerability functions reflecting design for site-specific hazard using Porter (2009a, b) methodology but with A_y and D_y reflecting site-specific ASCE 7-10 S_{DS} and S_{D1}	Consistent with design for site-specific seismic hazard that has been common since 2000. ASCE 7-10 S_{DS} and S_{D1}, more accurate	More effort. Uses 1990s-era pushover approximations of structural response.
3. Create new vulnerability functions using FEMA P-58 and the GEM component-based analytical vulnerability methodology (Porter et al. 2014).	Uses modern 2nd-generation performance-based earthquake engineering methods (like FEMA P-58) to reflect structural response, rigorous statistical surveys of building populations to quantify building diversity, and moment matching to propagate uncertainty. Most accurate.	No such category-based vulnerability functions for all U.S. building types have been created. Considering the 700,000 vulnerability functions required and the lack of automation to cate them, this option seems impractical for the present project.

Table 5-13. Options for seismic vulnerability of buildings.

5.7 Grants for Earthquake Mitigation

Supplementing available data. As in the 2005 *Mitigation Saves* study, the electronic data provide only a subset of the information required for a BCA. They do not include all of the grant application data that the grantee submitted on paper. Where the original electronic data contain precise addresses, participating agencies provided only approximate geolocation in order to protect personally identifiable information. They provided latitude and longitude to no more than 3 decimal places (approximately 100 meters) and no street number (e.g., at most street name). Many records in the database provide years in which the buildings were built, but none contains information about building type either before or after mitigation, beyond a description of the use to which the building is put, such as single-family dwelling. None provide the year in which the work was performed. Few include detailed descriptions of the work performed.

To satisfy its data needs, the project team reached out to some grantees to request additional information, but mostly acquired the necessary data via web searches. A great deal of information of many projects is available online in the form of scholarly journal articles, trade journal articles, news articles, press releases, and the web pages of companies that performed the work. These items provided many of the details of the mitigation effort and the year in which the mitigation was undertaken. In cases where the project team was unable to acquire sufficient data online about a project, it resampled, substituting a different project from the same value stratum.

The project team repeated the process of resampling until sufficient data were found for a project for each of the 25 strata.

The project team determined precise geographic locations for all sampled grants (generally to 4 or more decimal places, about 10m or less), estimated building area, number of stories, and model building types using Google Earth and Google Earth Street View.

One can estimate site soil classification for each building (an important variable for site hazard) using USGS's OpenSHA site data application tool, which draws on maps of site class by Wills and Clahan (2006) and Wald and Allen (2007).[20]

Characteristics of sampled projects. The project team sampled 23 high-hazard projects. The target was 25, but two very large projects cross four strata: 1) seismic retrofit of electrical substations in Los Angeles Department of Public Works and 2) replacement of pendant light fixtures in Los Angeles Unified School District. Together, these two projects represent approximately 15% of the total project amount. Figure 5-15 shows sample project locations. There were no projects in medium- or low-hazard regions, just as in the 2005 *Mitigation Saves* study. Other high-hazard grants include:

- Hospitals in San Francisco, Santa Ana, Norwalk, and Duarte, California; and, Olympia, WA.
- University classroom and administration buildings in Berkeley and San Bernardino, California.
- Civic centers in Pasadena, Berkeley, Huntington Beach, Santa Monica, and El Centro, California.
- Miscellaneous other public buildings such as a Seattle, WA, church and a city parking structure.

Of the 23 sampled projects, 18 deal with structural retrofit of existing buildings. The remainder deal with bracing ceilings in two hospital buildings and a county office building and replacing pendant light fixtures in schools. Of the 23 sampled projects, two are located in Washington, one in Oregon, and one in Utah. The remainder are located in California.

Methodology. To estimate most benefits, the project team used FEMA's BCA Tool version 5.3.0. Data requirements vary between different kinds of projects, but generally involve:

- Building location (address, latitude, and longitude)
- Project cost
- NEHRP site soil class (A, B, C, D, E, or F)
- Total building area
- Number of stories
- Total building replacement cost new
- Time-average number of occupants (averaging over time of day and day of week)
- Year of construction
- Building height

[20] Both those authorities have developed newer maps of site class, but neither has been implemented in OpenSHA. The incremental increase in accuracy might be significant for new design or possibly even single-site risk analysis, but probably does not matter in a portfolio risk analysis such as *Mitigation Saves Version 2*, where errors will tend to cancel out.

- Historical value
- Occupancy classification
- Code level, using FEMA's pre-code, low-code, moderate-code, high-code classification scheme (FEMA 2012e). Pre-code, for example, refers to a building that was designed and built without significant seismic design requirements, while high code refers generally to modern seismic design requirements, especially in high-seismicity areas.
- In some cases, other details such as: public service that the building provides (fire department, hospital, government service, etc.); population served; additional travel time to a similar nearby facility if this one is rendered inoperative; and annual budget.
- The user can optionally vary detailed engineering characteristics such as elastic period of vibration, deformation at which complete structural damage occurs, etc.

One enters the required data in a wizard-style user interface and then calculates EALs before and after mitigation using the standard method presented in Chapter 4: integrate hazard (the negative first derivative of exceedance rate of each of several levels of excitation) and vulnerability (the loss conditioned on excitation, as a fraction of value exposed) and multiply by value exposed. It estimates annualized losses in dollar equivalent terms, in each of seven categories: structural repair costs, two categories of nonstructural repair costs, acceptable costs to avoid statistical deaths and injuries, relocation costs, and two categories of losses associated with direct BI. It calculates the present value of losses before and after mitigation and the BCR.

The BCA Tool estimates direct BI losses but not indirect BI, so the project team applied the same method to the study of federal mitigation grants as for the study of exceeding building codes, estimating indirect BI as a factor *Q* of the cost of direct BI. See Appendix K, section K.1.8 for details.

The BCA Tool does not estimate loss of historic value or environmental damage. While several of the buildings in the earthquake sample are of historical value, the project team generally could not apply the method developed in the 2005 *Mitigation Saves* study to estimate the loss of historical value associated with damage, mostly because that method requires an estimate of the annual number of visitors to the facility. However, judging from the 2005 study, the loss of historic value is probably very small compared with other losses that are estimated here.

Figure 5-10. Locations of sample high-hazard earthquake mitigation projects.

Sample project data development. This section examines one project so that the reader can understand the methods used to fill in details that are missing from the grant database. Consider for example one building from a project to retrofit fire stations in Gresham, OR. FEMA data from pre-disaster mitigation grant PDMC-PJ-10-OR-2009-003 indicates that Station 74 is located somewhere on NE 192nd Ave near 45.533N, -122.466W, and was built in 1966. Using Google Earth and Google Earth Street View, the project team identified the street address as 1520 NE 192nd Ave., Gresham, OR 97230, at coordinates 45.5340N, -122.4658E; see Figure 5-11 for satellite and street views. With Google Earth, the project team estimated the building's plan area as approximately 4,700 sf. Based on street views and familiarity with common construction practices, one can estimate that the building resists lateral forces with reinforced masonry shearwalls and a flexible roof diaphragm (RM1 in FEMA terminology). According to the newspaper *DJC Oregon*, the project mitigated deficient roof-to-wall connections, a common problem with older RM1 buildings.

One can estimate the replacement cost (new) of the building using an RSMeans Square Foot Cost Manual, which provides a nationwide average per-square-foot cost for similar fire stations of $170 per square foot (2012 USD). RSMeans provides a location cost factor (accounting for local variations in construction cost) of 1.0. One can account for increases in construction costs between 2012 and 2016 using a deflator calculated as the ratio of national GDP PPP in 2016 to that in 2012. GDP data were acquired from the World Bank. The deflator suggests current costs 12% higher than in 2012. One can add another 100% of the building value to account for content value, including firefighting apparatus, which leads to an estimated replacement cost new of $380 per square foot, including contents and apparatus.

One can assign a pre-code Hazus design level to the pre-retrofit building in light of its 1966 year of construction and its location in Oregon. One can assign a post-retrofit design level of moderate code. The term "pre-code" suggests construction before seismic design provisions were adopted, at least for the subject building. The term "moderate code" means that the retrofit strengthens the new building, though probably not enough to satisfy requirements of the most recent building codes, since the project description speaks of modifications to the roof and roof-to-wall connections, but not of changes to wall reinforcement.

The total project amount is $617,000 which one can divide between the two buildings of this project in proportion to their plan area. Station 74 is estimated to have cost $353,000 to retrofit, or about $75 per square foot, which seems sufficient to strengthen the roof diaphragm and to connect the roof to the walls. The project team estimated average occupancy to be 10 people at all hours. A web search suggests that the station serves approximately 27,500 people (4 total stations serving a total population of 110,000 residents of Gresham, Oregon). If the station were rendered inoperative, apparatus from a nearby station would have to travel approximately 7.5 additional miles to serve buildings that would otherwise be served by station 74.

The project team estimated the present value of benefits for Gresham fire stations to be $3.9 million, mostly from reduced loss of service to the community in the event of an earthquake, and with small contributions from reduced property loss (about 1.2%) and reduced deaths and nonfatal injuries inside the stations (about 0.7%). The estimated BCR for this one project is 6.4.

A 

B

Figure 5-11. Gresham Fire Station 74 (A) in Google Earth Street View, and (B) from above.

5.8 Grants for Fire at the WUI

The database contains a total of 756 individual properties in a total of 114 grants. Two projects, both for retrofitting of private structures in Cook County, Minnesota, numbered 338 properties (45% of total), while representing only about 14% of the total cost. A sample of the database was extracted, first by hazard level (high, medium, and low) and then by 4% slices of total stratum cost, resulting in 75 samples. Of these, 28 contained sufficient information on which to base an estimate of project BCR. All but one of the projects had useful information on the Internet. The project team telephoned or emailed subgrantees for 21 of the 28 grants to obtain additional information. Several of the projects involved a relatively few structures. These included:

- Replacement of several older wood tanks with steel tanks in Calaveras County (California) Water District. The grant was for $1,160,000. The project team assumed maintenance would add $10,000 per year for the life of the project. The tanks serve an estimated 713 households with a population of 1,476. The FEMA BCA Tool (version 4.5.5, no longer available) estimated a project BCR of 2.5. The benefit derives from avoiding the loss of revenue from 20% of customers for an extended period following wildfires where mean recurrence interval varies between 6 and 40 years. It also assumes the BCA Tool's internal discount rate of 7%. This benefit is based on the (unstated) assumption that the wood tanks are flammable, while the new steel tanks are not vulnerable to fire if supplied with a defensible space. The benefit estimate, however, excludes the improved water supply to the customers, which would provide firefighting water supply for at least some houses. Assuming improved water supply is available to half the 20% of customers, the project team estimated an added benefit of $14 million using FEMA's BCA Tool (version 5.3) using the same 7% discount rate. That is, the addition reflects protecting 70 houses and the associated occupant death and injury, as well as the loss of revenue. In the *2017 Interim Report*, the discount rate is taken as approximately 2.2% rather than 7%, which resulted in a final estimated benefit of almost $32 million, resulting in a BCR of 24. (Chapter 2 presents BCRs based on 3% and 7% discount rates, consistent with OMB procedures.)

- Wildfire protection for the Virginia Harris Cockrell Cancer Research Center in Smithville, Texas. A component of the University of Texas M.D. Anderson Cancer Research Center, the center lies on a tract of 713 acres with a high wildfire risk, as defined by the Southern Wildfire Risk Assessment. This risk has been evident in recent years: a number of significant wildfires have occurred near the facility. The mitigation strategy to protect the center from wildfire damage included establishing more than 23 acres of zone-2 and zone-3 defensible areas surrounding the property, and hardening and fire-proofing the exterior of the Griffin Building, which houses the research animals used by the center. The project cost $1.975 million. The project also installed a wildfire sprinkler system on the exterior of the Griffin Building, which is fully automated and independent of public power and water sources. This project created a strong barrier to the onset of wildfires, in particular protecting the research animals, which are of great value. The applicant evaluated the project in 2010 using the FEMA BCA Tool (version 4.1.3) and found an overall BCR of 7.7. The current FEMA BCA Tool (version 5.3) does not seem to be able to handle this project (it lacks fire data). USFS BPs for this site and methods developed in the study of above-code benefits of this project both suggest a BCR of less than 1.

- Creation of defensible space and replacement of 410 window units on the five-story Mt. St. Francis nursing home in Colorado Springs (Colorado), which was built in 1915 for a total project cost of $420,000. These improvements permit sheltering in place of the nursing home patients and staff, rather than requiring staff and residents to evacuate in case of wildfire. Detailed data for the facility were unavailable, but given that the facility has 108 beds the project team estimated the total facility to have a replacement cost (new) of $30 million. Using the FEMA BCA Tool version 5.3 with a discount rate of 2.13%, the project team estimated a BCR of 10.5. This value does not account for the costs to evacuate elderly patients nor the frailty of the patients—meaning that evacuating them might hurt them. If the project team were able to include the benefit associated with a lower chance of harm during evacuation (because evacuation would be unnecessary), the BCR would be higher.

With a few exceptions, the data that FEMA was able to provide on remaining projects contained insufficient information to directly determine BCRs. For example, a number of projects involved private residential roof replacement—that is, replacing a combustible wood shake roof with a non-combustible roof. In these programs, homeowners typically received 70% of the new roof cost up to a maximum (typically) of $7,500. In many cases and for various reasons, homeowners opted to spend substantially more than this, but the total amount spent is not recorded in the project's electronic data. Without cost, one cannot estimate a BCR. Incidentally, to qualify for this roof subsidy, the homeowner was typically required to have, or newly create, a defensible space around the home (a not inconsiderable expense). Several other programs consisted solely of vegetation management of public or private lands and, in a few cases, subsidies for residential sprinklers. In all these cases, the project data contained insufficient data to directly estimate a BCR.

6 References

(ADB) Asian Development Bank (1999). *Handbook for the Economic Analysis of Water Supply Project*s. http://www.susana.org/_resources/documents/default/2-510-adb-1999-handbook-economic-analysis-of-ws-projects.pdf.

AdvisoryHQ (2017). *2017 Guide: Finding the Best Commercial Mortgage Rates & Real Estate Loan Rates*. https://www.advisoryhq.com/articles/commercial-real-estate-loan-rates/. [accessed 6 December 2017]

Ahern, M., Kovats, R.S., Wilkinson, P., Few, R., and Matthies, F. (2005). Global health impacts of floods: epidemiologic evidence. Epidemiologic reviews, 27(1), 36-46.

Allianz Global Corporate and Specialty (2015). Business Interruption Claims on the Rise. *Insurance Journal*. http://www.insurancejournal.com/news/international/2015/12/10/391437.htm. [accessed 31 July 2017].

American Wood Council (2015). *Wood Frame Construction Manual (WFCM) for One- and Two-Family Dwellings*. Wood Design Standards Committee, 314 p. http://www.awc.org/pdf/codes-standards/publications/wfcm/AWC-WFCM2015-ViewOnly-1510.pdf [accessed 14 November 2016]

Anderson C., Santos J.R., and Haimes Y.Y. (2007). A risk-based input-output methodology for measuring the effects of the August 2003 northeast blackout. *Economic Systems Research*, *19*, 183-204.

Angies List (2013). *How Much Does It Cost to Build a Handicap Accessible Ramp?* http://answers.angieslist.com/how-cost-build-handicap-accessible-ramp-q48414.aspx. [accessed 6 December 2017]

Applied Technology Council (1991). *Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States*, *FEMA 224*. Federal Emergency Management Agency, Washington, DC. http://www.fema.gov/plan/prevent/earthquake/pdf/fema-224.pdf [viewed 6 June 2006], http://www.fema.gov/plan/prevent/earthquake/professionals.shtm [accessed 6 June 2006]

Applied Technology Council (2005). *ATC-20-1: Field Manual: Postearthquake Safety Evaluation of Buildings*, 2nd Edition, Redwood City, CA, 144 pp.

Applied Technology Council (2009). *Quantification of Building Seismic Performance Factors. FEMA P-695*, Federal Emergency Management Agency, Washington, DC, 421 pp.

Applied Technology Council (2012). *Seismic Performance Assessment of Buildings Volume 1 – Methodology FEMA P-58-1*. Federal Emergency Management Agency, Washington, DC, https://www.fema.gov/media-library-data/1396495019848-0c9252aac91dd1854dc378feb9e69216/FEMAP-58_Volume1_508.pdf [accessed 08 Dec 2016]

Applied Technology Council, Scawthorn, C., Khater, M., Rojahn, C., & Cluff, L. S. (1991). *Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States*. Applied Technology Council.

(ASCE/SEI) American Society of Civil Engineers Structural Engineering Institute (2010). *Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10*, Reston VA, 608 pp

(ASCE/SEI) American Society of Civil Engineers Structural Engineering Institute (2017). *Minimum Design Loads for Buildings and Other Structures*. *ASCE/SEI Standard 7-16*.

(ASCE) American Society of Civil Engineers (2013). *Seismic Rehabilitation of Existing Buildings*. *ASCE/SEI Standard 41-13*.

(ASCE) American Society of Civil Engineers (2014), *Flood Resistant Design and Construction*, *ASCE/SEI Standard 24-14*.

(ASCE) American Society of Civil Engineers. Unpublished. *Preliminary Minimum Design Loads for Buildings and Other Structures. ASCE/SEI Standard 7-16*. Provided by Peter Vickery, ARA, Raleigh N.C.

(ASFPM) Association of State Floodplain Managers. (2013). *NAI How-to Guide for Mitigation*, Madison, WI, 76 p. Retrieved from http://www.floods.org/ace-images/ASFPM-MitigationFinalJuly28.pdf. [accessed 30 Jan 2017].

(ARA) Applied Research Associates (2008). *Florida Residential Wind Loss Mitigation Study*. https://www.floir.com/siteDocuments/ARALossMitigationStudy.pdf.

Association for the Advancement of Automotive Medicine (2001). *Abbreviated Injury Scale (AIS) 1990 - Update 98*, Barrington IL, 68 pp.

Awondo, S., Hollans, H., Powell, L., and Wade, C. (n.d.). *Estimating the Effect of FORTIFIED Home TM Construction on Home Resale Value.* Alabama Center for Information and Insurance Research (ACIIR), Culverhouse College of Commerce, Tuscaloosa, AL 35487. 6 pp.

(BEA) Bureau of Economic Analysis (2016), *Input-Output Accounts Data*. https://bea.gov/industry/io_annual.htm. [accessed 19 December 2017]

Berko, J., Ingram, D.D., Saha, S., and Parker, J.D. (2014). Deaths attributed to heat, cold, and other weather events in the United States, 2006–2010. *National Health Statistics Reports* 76. Hyattsville, MD: National Center for Health Statistics, https://www.cdc.gov/nchs/data/nhsr/nhsr076.pdf [accessed 29 Aug 2017].

Birchard, K., Storesund, R., and Buck, S. (2016). *Flood Control 2.0: Economic Analysis, Guidebook for Economic Analysis of Flood Control Alternatives*, The Integrative Economics, LLC.

Bloom, D.E., Caero, E.T., Jané-Llopis, E., Abrahams-Gessel, S., Bloom, L.R., Fathima, S., Feigl, A.B., Gaziano, T., Mowa, M., Pandya, A., Prettner, K., Rosenberg, L., Seligman, B., Stein, A.Z., and Weinstein, C. (2011). *The Global Economic Burden of Noncommunicable Diseases*. Geneva: World Economic Forum. 46 p.

Bolen, W. (2001). *Sand and Gravel, Construction*. U.S. Geological Survey. 2001. https://minerals.usgs.gov/minerals/pubs/commodity/sand_&_gravel_construction/sandmyb01.pdf.

Börjesson, P., and Gustavsson, L. (2000). Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. *Energy Policy* 28 (9): 575-588.

Building Officials and Code Administrators International Inc. (1950). *The BOCA National Building Code*. Country Club Hills, IL: Building Officials and Code Administrators International Inc.

Burby, R.J. (2006). Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas. *The Annals of the American Academy of Political and Social Science*, 604 (1), 171-191.

Burby, R.J., May, P.J., Malizia, E.E., and Levine, J. (2000). Building code enforcement burdens and central city decline. *Journal of the American Planning Association*, 66(2), 143-161.

Bureau of Labor Statistics (2017a). *Economy at a Glance*. https://www.bls.gov/eag/home.htm. [accessed December 6, 2017]

Bureau of Labor Statistics (2017b). *Employment, Hours, and Earnings from the Current Employment Statistics survey (National)*. https://data.bls.gov/timeseries/CES2000000001?data_tool=XGtable. [accessed December 6, 2017]

Byram, G. M. (1959). Combustion of forest fuels. Pp. 61-89. in *Forest Fire: Control and Use*, 2nd edition. New York: McGraw-Hill.

CalTech Design and Construction (2014). *Appendix VII A Note on Earthquake Design of CalTech Buildings*. Pasadena, CA: California Institute of Technology, https://www.dandc.caltech.edu/documents/113-caltech_appendix_vii.pdf.

Caton, S. E., Hakes, R. S., Gorham, D. J., Zhou, A., and Gollner, M. J. (2017). Review of pathways for building fire spread in the wildland urban interface part I: exposure conditions. *Fire Technology*, 53 (2), 429-473.

Chen, K., and McAneney, J. (2004). Quantifying bushfire penetration into urban areas in Australia. *Geophysical Research Letters*, 31:L12212.

Chopra, A., and Goel, R. (2000). Building period formulas for estimating seismic displacements. *Earthquake Spectra* 16 (2), 533-536.

Christopoulos, C., Filiatrault, A., Uang, C.M., and Folz, B. (2002). Posttensioned energy dissipating connections for moment-resisting steel frames. *Journal of Structural Engineering*, 128(9), 1111-1120.

City of Moore (2014a). "City Adopts New Building Codes, First in the Nation." https://www.cityofmoore.com/node/2111 [accessed November 8, 2017].

City of Moore (2014b). *City of Moore Municipal Code*. https://library.municode.com/ok/moore/codes/code_of_ordinances?nodeId=COOR_PT5BURECO_CH2BUCORE_ARTABUCO_S5-202AMBUCO [accessed November 8, 2017].

Clinton, W.J. (1994). Executive Order #12893 Principles for Federal Infrastructure Investments, Washington, DC.

Cohen, J.D. (1995). Structure ignition assessment model (SIAM). Weise, D.R. and Martin, R.E., technical coordinators. *Proceedings of the Biswell symposium: Fire Issues and Solutions in Urban Interface and Wildland Ecosystems*: 15-17.

Constantinou, M.C., Soong, T.T., and Dargush, G.F. (1998). *Passive Energy Dissipation Systems for Structural Design and Retrofit*. Buffalo, New York: Multidisciplinary Center for Earthquake Engineering Research.

Cook, J., Oreskes, N., Doran, P. T., Anderegg, W. R., Verheggen, B., Maibach, E. W. and Nuccitelli, D. (2016). Consensus on consensus: a synthesis of consensus estimates on human-caused global warming. *Environmental Research Letters*, 11(4), 048002.

Dietzenbacher, E., and Lahr, M. L. (2004). *Wassily Leontief and input-output economics*. Cambridge, UK: Cambridge University Press.

DJC Oregon (2010). "Gresham Updating Fire Stations." http://djcoregon.com/news/2010/08/26/gresham-upgrading-fire-stations/ [accessed November 12, 2017].

Drysdale, D. (1999). *An Introduction to Fire Dynamics*. Chichester, New York: Wiley.

Eckstein, O. (1958). *Water Resource Development: The Economics of Project Evaluation*, Otto Eckstein. Cambridge: Harvard University Press.

Emanuel, K. A. (2013). Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences*, 110(30), 12219-12224.

Federal Reserve Bank of St. Louis. *Gross Domestic Product: Implicit Price Deflator*. https://fred.stlouisfed.org/series/GDPDEF/. [accessed 5 December 2017]

(FEMA) Federal Emergency Management Agency (2003). *Flood Insurance Study: Horry County, South Carolina and Incorporated Areas*, Flood Insurance Study Number 45051CV000A.

(FEMA) Federal Emergency Management Agency (2006a). *Flood Insurance Study: A Report of Flood Hazards in Dare County, North Carolina and Incorporated Areas*, Flood Insurance Study Number 37055CV000A.

(FEMA) Federal Emergency Management Agency (2006b). *Flood Insurance Study: Santa Rosa County, Florida and Incorporated Areas*, Flood Insurance Study Number 12113CV000A.

(FEMA) Federal Emergency Management Agency (2006c). *Multi-hazard Loss Estimation Methodology - Flood Model: HAZUS-MH Technical Manual*.

(FEMA) Federal Emergency Management Agency (2007a). *Design Guide for Improving Hospital Safety in Earthquakes, Floods and High Winds: Providing Protection to People and Buildings*, FEMA 577.

(FEMA) Federal Emergency Management Agency (2007b). *Flood Insurance Study: Gulf County, Florida and Incorporated Areas*, Flood Insurance Study Number 12045CV000B.

(FEMA) Federal Emergency Management Agency (2007c). *Flood Insurance Study-Preliminary: James City County, Virginia and Incorporated Areas*, Flood Insurance Study Number 51095CV000A.

(FEMA) Federal Emergency Management Agency (2007d). *Design Guide for Improving Critical Facility Safety from Flooding and High Winds: Providing Protection to People and Buildings*, FEMA 543.

(FEMA) Federal Emergency Management Agency (2008a). *2008 Supplement to the 2006 Evaluation of the National Flood Insurance Program's Building Standards*. Washington, DC, 14 p. Retrieved from https://www.fema.gov/media-library-data/20130726-1911-25045-9876/2008_freeboard_report.pdf [accessed 13 January 2017].

(FEMA) Federal Emergency Management Agency (2008b). *Flood Damage-Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in accordance with the National Flood Insurance Program, FEMA Technical Bulletin 2*. Washington, DC, 20 p. Retrieved from http://www.jacksonms.gov/DocumentCenter/View/440 [accessed January 25 2017].

(FEMA) Federal Emergency Management Agency (2008c). *Flood Insurance Study: Lee County, Florida and Incorporated Areas*, Flood Insurance Study Number 12071CV001A.

(FEMA) Federal Emergency Management Agency (2008d). *Flood Insurance Study-Preliminary: Lafourche Parish, Louisiana and Incorporated Areas*, Flood Insurance Study Number 22057CV000A.

(FEMA) Federal Emergency Management Agency (2009a). *Flood Insurance Study: Bay County, Florida and Incorporated Areas*, Flood Insurance Study Number 12005CV000B.

(FEMA) Federal Emergency Management Agency (2009b). *Flood Insurance Study: Pinellas County, Florida and Incorporated Areas*, Flood Insurance Study Number 12103CV000C.

(FEMA) Federal Emergency Management Agency (2009c). *Quantification of Building Seismic Performance Factors*, FEMA P-695.

(FEMA) Federal Emergency Management Agency (2009d). *Recommended Residential Construction for Coastal Areas: Building on Strong and Safe Foundations*, FEMA P-550.

(FEMA) Federal Emergency Management Agency (2010). *Design Guide for Improving School Safety in Earthquakes, Floods and High Winds,* FEMA P-424.

(FEMA) Federal Emergency Management Agency (2011a). *Coastal Construction Manual. Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas* (Fourth Edition) FEMA P-55/Volume II.

(FEMA) Federal Emergency Management Agency (2011b). *Multi-hazard Loss Estimation Methodology Flood Model Hazus®-MH 2.1 Technical Manual.* Federal Emergency Management Agency, Washington, DC, 569 pp.

(FEMA) Federal Emergency Management Agency (2012a). *Flood Insurance Study: Collier County, Florida*, Flood Insurance Study Number 12021CV000B.

(FEMA) Federal Emergency Management Agency (2012b). *Flood Insurance Study-Preliminary: Calhoun County, Texas and Incorporated Areas*, Flood Insurance Study Number 48057CV001A.

(FEMA) Federal Emergency Management Agency (2012c). *Flood Insurance Study-Preliminary: Jefferson County, Texas and Incorporated Areas,* Flood Insurance Study Number 48245CV000A.

(FEMA) Federal Emergency Management Agency (2012d). *FEMA P-58-1: Seismic Performance Assessment of Buildings. Volume 1–Methodology*. Washington, DC.

(FEMA) Federal Emergency Management Agency (2012). *Multi-hazard Loss Estimation Methodology Earthquake Model Hazus®-MH 2.1 Technical Manual.* Federal Emergency Management Agency, Washington, DC, 718 pp.

(FEMA) Federal Emergency Management Agency (2013a). *Flood Insurance Study-Preliminary: Hudson County, New Jersey (all Jurisdictions),* Flood Insurance Study Number 34017CV000B.

(FEMA) Federal Emergency Management Agency (2013b). *Including Building Codes in the National Flood Insurance Program: Fiscal Year 2013 Report to Congress Impact Study for Biggert-Waters Flood Insurance Reform Act of 2012*. Washington, DC, 58 p.

(FEMA) Federal Emergency Management Agency (2013c). *Integrating Hazard Mitigation Into Local Planning Case Studies and Tools for Community Officials,* Washington, DC, 84 p. Retrieved from http://www.gema.ga.gov/Mitigation/Resource%20Document%20Library/Integrating%20Hazard%20Mitigation%20into%20Local%20Planning.pdf. [accessed 30 January 2017].

(FEMA) Federal Emergency Management Agency (2013d) *Budget*, https://www.fema.gov/pdf/about/budget/fema_fy2013_bib.pdf. [accessed 4 September 2017].

(FEMA) Federal Emergency Management Agency (2014a). *National Flood Insurance Program Floodplain Management Standards Losses Avoided Study*. P-23.

(FEMA) Federal Emergency Management Agency (2014b). *Flood Insurance Study: Lancaster County, Virginia and Incorporated Areas*, Flood Insurance Study Number 51103CV000B.

(FEMA) Federal Emergency Management Agency (2014c). *Flood Insurance Study-Revised Preliminary: Palm Beach County, Florida and Incorporated Areas*, Flood Insurance Study Number 12099CV000A.

(FEMA) Federal Emergency Management Agency (2014d). *National Flood Hazard Layer*. Retrieved from https://msc.fema.gov/portal.

(FEMA) Federal Emergency Management Agency (2014e). *Phase 3 National Methodology and Phase 2 Regional Study Losses Avoided as a Result of Adopting and Enforcing Hazard-Resistant Building Codes*. Washington, DC, 412 p.

(FEMA) Federal Emergency Management Agency (2014f), *Taking Shelter from the Storm: Building a Safe Room for Your Home or Small Business*. P-320. https://www.fema.gov/fema-p-320-taking-shelter-storm-building-safe-room-your-home-or-small-business. [accessed 18 January 2017].

(FEMA) Federal Emergency Management Agency (2015a). *Reducing Flood Risk to Residential Buildings That Cannot Be Elevated*. *FEMA P-1037*, 12 p. Retrieved from https://www.fema.gov/media-library-data/1443014398612-4dfc0f86711bc72434b82c4b100a677/revFEMA_HMA_Grants_4pg_2015_508.pdf. [accessed 25 January 2017].

(FEMA) Federal Emergency Management Agency (2015b). *Flood Resistant Provisions of the 2015 International Codes*. 51 p. Retrieved from https://www.fema.gov/media-library-data/1446030649587-10e447987a16b1313253361ed0871a46/2015_Icodes_Flood_Provisions_508_v2.pdf. [accessed 20 January 2017].

(FEMA) Federal Emergency Management Agency (2015c). *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms, Third Edition*. P-361. https://www.fema.gov/media-library/assets/documents/3140.

(FEMA) Federal Emergency Management Agency (2015d). *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures (FEMA P-1050-1)*. Federal Emergency Management Agency. Washington, DC. 515 pp.

(FEMA) Federal Emergency Management Agency (2015e). *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook Third Edition.* P-154. https://www.fema.gov/media-library-data/1426210695633-d9a280e72b32872161efab26a602283b/FEMAP-154_508.pdf

(FEMA) Federal Emergency Management Agency (2016a). *Loss Dollars Paid by Calendar Year*. Retrieved from https://www.fema.gov/loss-dollars-paid-calendar-year. [accessed 30 January 2017].

(FEMA) Federal Emergency Management Agency (2016b). *Disaster Relief Funding: FY 2017 Funding Requirements*. February 9, 2016. https://www.dhs.gov/sites/default/files/publications/FEMA%20-%20Disaster%20Relief%20Fund%20-%20Annual%20Report%20-%20%20FY%202017%20Funding%20Requirements_0.pdf.

(FEMA) Federal Emergency Management Agency (2017a). *Public Assistance Program and Policy Guide, FP 104-009-2.* Washington, DC, 217 p.

(FEMA) Federal Emergency Management Agency (2017b). *FEMA HMGP Property Acquisitions*. Retrieved from https://www.fema.gov/media-library/assets/documents/85455 [accessed 30 January 2017]

(FEMA) Federal Emergency Management Agency (2017c) *National Flood Hazard Layer.* https://msc.fema.gov/portal.

Field, E. H., Biasi, G. P., Bird, P., Dawson, T. E., Felzer, K. R., Jackson, D. D., Johnson, K. M., Jordan, T. H. Madden, C., Michael, A. J., Milner, K. R., Page, M. T., Parsons, T., Powers, P. M., Shaw, B. E., Thatcher, W. R., Weldon II, R. J., and Zeng, Y. (2015). Long-term time-dependent probabilities for the third uniform California earthquake rupture forecast (UCERF3). *Bulletin of the Seismological Society of America,* 105 (2A): 1-33, April 2015, doi: 10.1785/0120140093.

Finn, D., Chandrasekhar, D., and Xiao Y. (2016). Planning for resilience in the New York metro region after Hurricane Sandy: International and Comparative Perspectives. In book: *Spatial Planning and Resilience Following Disasters* (pp.117-136). Bristol, UK: Policy Press.

Finney, M. A., C. W. McHugh, I. C. Grenfell, K. L. Riley, and K. C. Short. 2011. "A simulation of probabilistic wildfire risk components for the continental United States." Stoch Environ Res Risk Assess 25.

Fothergill, A., and Peek, L. (2004). Poverty and disasters in the United States: a review of recent sociological findings. *Natural Hazards* 32: 89-110.

(GAO) Government Accountability Office (2014). *Hurricane Sandy: FEMA Has Improved Disaster Aid Verification but Could Act to Further Limit Improper Assistance*. GAO 15-15. December 2014. http://www.gao.gov/assets/670/667469.pdf.

Government Publishing Office (2016). Federal Register Notices, 81: 5487- 5488. Retrieved from https://www.gpo.gov/fdsys/pkg/FR-2016-02-02/pdf/2016-01604.pdf [accessed 24 September 2017].

Haimes, Y.Y. and Jiang P. (2001). Leontief-Based Model of Risk in Complex Interconnected Infrastructures. *Journal of Infrastructure Systems*, 7, 1-12.

Haimes, Y.Y., Horowitz, B.M., Lambert, J.H., Santos, J.R., Crowther, K., and Lian C. (2005). Inoperability input-output model for interdependent infrastructure sectors. I: theory and methodology. *Journal of Infrastructure Systems*, 11, 67-79.

Hakes, R.S.P., Caton, S.E., Gorham, D.J., and Gollner, M.J. (2017). A review of pathways for building fire spread in the wildland urban interface part ii: response of components and systems and mitigation strategies in the United States. *Fire Technology* 53 (2): 475-515.

Himoto, K., and Tanaka, T. (2008). Development and validation of a physics-based urban fire spread model. *Fire Safety Journal* 43: 477-494.

Holling, C. (1973). Resilience and stability of ecological Systems. *Annual Review of Ecology and Systematics*, 4, 1–23.

IAWF (2013). *WUI Fact Sheet*. Pp. 11. Missoula: International Association of Wildland Fire. Updated August 1, 2013, Used by permission from ICC and NARCD Councils from the national program Wildfire, Safe, Sound and Code Smart® program. This document is a condensed version of the original document. http://www.iawfonline.org/pdf/WUI_Fact_Sheet_08012013.pdf.

(IBHS) Insurance Institute for Business & Home Safety (2012). *FORTIFIED HOME Hurricane Standards*. https://disastersafety.org/wp-content/uploads/fortified-home-hurricane-standards.pdf

(IBHS) Insurance Institute for Business & Home Safety (2015). *FORTIFIED HOME High Wind Standards*. http://disastersafety.org/wp-content/uploads/2015/07/FORTIFIED-High-Wind-Standards-2015.pdf.

IBM (2016). *Federal Emergency Management Agency (FEMA) Enterprise Applications Development Integration and Sustainment (EADIS) Task Order HSFEHQ-08-J-2009 Public Assistance (PA) System Design Document Work Order 05 – Enterprise Data Warehouse (EDW) Version 3.7 August 9, 2016*. FEMA, Washington, DC, 157 pp.

(ICBO) International Conference of Building Officials (1927). *Uniform Building Code*. Long Beach, CA, 256 pp.

(ICC) International Code Council (2014a). *ICC/NSSA Standard for the Design and Construction of Storm Shelters. Standard ICC 500-2014*.

(ICC) International Code Council (2015a). *2015 International Building Code*. Country Club Hills, IL, 700 pp.

(ICC) International Code Council (2015b). *2015 International Residential Code for One- and Two-Family Dwellings*. Falls Church, VA, 932 pp.

(ICC) International Code Council (2015c). *2015 International Wildland-Urban Interface Code*. Falls Church, VA, 74 pp.

(ICC) International Code Council (2015d). *2015 International Existing Building Code*. Falls Church, VA, 304 pp.

(ICC) International Code Council. (2014). *Reducing Flood Losses Through the International Codes®: Coordinating Building Codes and Floodplain Management Regulations, 4th edition*. Washington, DC, 150 p., https://www.fema.gov/media-library-data/1411731781834-d0c7d7f9ff0d195ce3c33901ba73daac/ReducingFloodLosses_4thED_Final_508.pdf [accessed 29 January 2017].

(III) Insurance Information Institute (2006-2015) *Components of The Combined Ratio, Property/Casualty Insurance, 2006-2015 (1)*, https://www.iii.org/table-archive/21061. [accessed 20 June 2017].

(IPCC) Intergovernmental Panel on Climate Change (1992). *Climate Change 1992.* Houghton, J. T., and Callander, B. A., eds., Cambridge University Press.

(IPCC) Intergovernmental Panel on Climate Change (1995). *Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (Vol. 2). Houghton, J. T., ed. Cambridge University Press.

(IPCC) Intergovernmental Panel on Climate Change (2001). *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Core Writing Team, Watson, R. T., and Albritton, D. L. eds., Cambridge University Press.

(IPCC) Intergovernmental Panel on Climate Change (2007). *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Core Writing Team, Pachauri, R.K. and Reisinger, A. (Eds.)., IPCC, Geneva, Switzerland. 104 pp.

(IPCC) Intergovernmental Panel on Climate Change (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf. [accessed 25 January 2017].

Isard, W. (1960). *Methods of regional analysis: An introduction to regional science*. Cambridge, MA: MIT Press.

Jones, C.P., Coulbourne, W.L., Marshall, J., and Rogers, Jr, S.M. (2006). *Evaluation of the National Flood Insurance Program's Building Standards*, Durham, NC, 118p. Retrieved from https://www.fema.gov/media-library-data/20130726-1602-20490-5110/nfip_eval_building_standards.pdf. [accessed 13 January 2017].

Kirtman, B., Power, S.B., Adedoyin, J.A., Boer, G. J., Bojariu, R., Camilloni, I., Doblas-Reyes, F.J., Fiore, A.M., Kimoto, M., Meehl, M., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenborgh, G. J., Vecchi G., and Wang, H.J. (2013). Near-term climate change: projections and predictability. In Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, eds., *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K., and Sugi, M. (2010). Tropical cyclones and climate change. *Nature Geoscience*, 3(3), 157-163.

Koo, E., Pagni, P.J., Weise, D.R., and Woycheese, J.P. (2010). Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire*, 19: 818-843.

Kousky, C., and Walls, M. (2014). Floodplain conservation as a flood mitigation strategy: Examining costs and benefits. *Ecological Economics*. 104: 119-128.

Krawinkler, H., Aslani, H., Baker, J., Cornell, C.A., Heintz, J., Hutchinson, T., Ince, U., Kramer, S., Kutter, B., Lowes, L., Martin, G., Meszaros, J., Miranda, E., Nagae, T., Pekelnicky, R., Porter, K., Shoaf, K., Seligson, H., Somerville, P., and Zareian, F. (2005). Van Nuys Hotel Building Testbed Report: Exercising Seismic Performance Assessment, Report 2005-11, Pacific Earthquake Engineering Research Center, Richmond, CA, http://peer.berkeley.edu/publications/peer_reports/reports_2005/PEER_511_KRAWINKLER_testbed.pdf.

Krayer, W.R., and Marshall, R.D. (1992). Gust factors applied to hurricane winds. *Bull. Am. Meteorol. Soc.*, *73* (5), 613–617.

Kundzewicz, Z.W., Lugeri, N., Dankers, R., Hirabayashi, Y., Döll, P., Pińskwar, I., Dysarz, T., Hochrainer, S., and Matczak, P. (2010). Assessing river flood risk and adaptation in Europe - review of projections for the future. *Mitigation and Adaptation Strategies for Global Change*. 15 (7): 641-656.

Lee, S., Davidson, R., Ohnishi, N., and Scawthorn, C. (2008). Fire following earthquake, reviewing the state-of-the-art of modeling. *Earthquake Spectra* 24 (4): 933-967.

Leontief, W. (1936). Quantitative input and output relations in the economic system of the United States. *Review of Economics and Statistics*, *18*, 105-125.

Lian C., Santos, J.R., and Haimes, Y.Y. (2007). Extreme risk analysis of interdependent economic and infrastructure sectors, *Risk Analysis, an International Journal*, *27*, 1053-1064.

Lian, C., and Haimes, Y.Y. (2006). Managing the risk of terrorism to interdependent infrastructure systems through the dynamic inoperability input-output model. *Systems Engineering*, *9*, 241-258.

Life Insurance Selling Magazine (2013). *Life Insurance by the Numbers*. August 26, 2013. http://www.thinkadvisor.com/2013/08/26/life-insurance-by-the-numbers. [accessed 6 December 2017].

LIMRA (2016). *Life Insurance Ownership in Focus (2016)*. September 28, 2016. http://www.limra.com/ownership/. [accessed 6 December 2017].

Luco, N., Ellingwood, B.R., Hamburger, R.O., Hooper, J.D., Kimball, J.K. and Kircher, C.A. (2007). Risk-targeted versus current seismic design maps for the conterminous United States. *Structural Engineers Association of California 2007 Convention Proceedings, 26-29 Sep 2007, Lake Tahoe CA*, 163-175.

Maass, A., Hufschmidt, M.M., Dorfman, R., Thomas, Jr., H.A., Marglin S.A., and Maskew Fair, G., (1962). *Design of Water-Resource Systems: New Techniques for Relating Economic Objectives, Engineering Analysis, and Governmental Planning*, Cambridge, MA, Harvard University Press.

Manzello, S. L., Cleary, T.G., Shields, J.R., and Yang, J.C. (2005). Urban-wildland fires: on the ignition of surfaces by embers. In Turns, S., ed. *Proceedings of the 4th Joint Meeting of the U.S. Sections of Combustion Institute.*

Manzello, S. L., Cleary, T. G., Shields, J. R., and Yang, J. C. (2006a). Ignition of mulch and grasses by firebrands in wildland-urban interface fires. *International Journal of Wildland Fire* 15: 427-431.

Manzello, S. L., Cleary, T. G., Shields, J. R., and Yang, J. C. (2006b). On the ignition of fuel beds by firebrands. *Fire and Materials* 30 (1): 77-87.

Manzello, S. L., Shields, J. R. and Cleary, T. G. (2005). *Ignition of Mulch by Firebrands in Wildland/Urban Interface (WUI) Fires*.

Maranghides, A., McNamara, D., Vihnanek, R., Restaino, J., and Carrie Leland Excet, I. S., VA. 2015. *A Case Study of a Community Affected by the Waldo Fire - Event Timeline and Defensive Actions*: 227: NIST Technical Note 1910, This publication is available free of charge from: http://dx.doi.org/10.6028/NIST.TN.1910.

Martinuzzi, S., Stewart, S.I., Helmers, D.P., Mockrin, M.H., Hammer, R.B., and Radeloff, V.C. (2015a). *The 2010 Wildland-Urban Interface of the Conterminous United States - Geospatial Data*. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2015-0012.

Martinuzzi, S., Stewart, S.I., Helmers, D.P., Mockrin, M.H., Hammer, R.B., and Radeloff, V.C. (2015b). *The 2010 Wildland-Urban Interface of the Conterminous United States.* 124 p. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.

Mayes, R.L., Jones, L.R., and Kelly, T.E. (1990). The economics of seismic isolation in buildings. *Earthquake Spectra*, 6(2), 245-263.

McMahon T.M., and Friedman, D.J. (2016). Havoc in the supply chain tests business interruption policies. *Business Insurance*, 27 Mar 2016, http://www.businessinsurance.com/article/00010101/STORY/303279991/Havoc-in-the-supply-chain-tests-business-interruption-policies. [accessed 15 October 2017].

Mell, W.E., Manzello, S.L., Maranghides, A., Butry, D., and Rehm, R.G. (2010). The wildland–urban interface fire problem–current approaches and research needs. *International Journal of Wildland Fire*, *19*(2), 238-251.

Miller, R.E., and Blair, P.D. (2009). *Input-output Analysis: Foundations and Extensions, 2nd ed.* NJ: Cambridge University Press.

(MMC and CFIRE) Multihazard Mitigation Council and Council on Finance, Insurance, and Real Estate (2015). *Developing Pre-Disaster Resilience Based on Public and Private Incentivization*. National Institute of Building Sciences, Washington, DC, 57 p. https://www.nibs.org/resource/resmgr/MMC/MMC_ResilienceIncentivesWP. [accessed 16 October 2017].

(MMC) Multihazard Mitigation Council. (2005). *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*. National Institute of Building Sciences, Washington, DC.

Mullin, E. (2013). “How to Pay for Nursing Home Costs.” *U.S. News and World Report*. February 26, 2013. https://health.usnews.com/health-news/best-nursing-homes/articles/2013/02/26/how-to-pay-for-nursing-home-costs. [accessed 5 December 2017].

(NAHB) National Association of Homebuilders (2015). *Cost of Constructing a Home*. https://www.nahbclassic.org/generic.aspx?genericContentID=248306 [accessed 22 December 2017].

NASA Jet Propulsion Laboratory (2017). *Scientific Consensus: Earth's Climate is Warming*. Pasadena CA, 15 p. http://climate.nasa.gov/scientific-consensus/ [accessed 25 January 2017].

National Center for Environmental Economics (2010). *Guidelines for Preparing Economic Analyses*, Office of Policy, United States Environmental Protection Agency. December 17, 2010.

National Fire Protection Association (2013). *White Paper on Upholstered Furniture Flammability*. Quincy, MA, 32pp.

(NCSU) NC State University College of Design, Center for Universal Design (2004). *Wood Ramp Design: How to Add a Ramp that Looks Good and Works Too*. https://projects.ncsu.edu/ncsu/design/cud/pubs_p/docs/rampbooklet296final.pdf.

NEHRP Consultants Joint Venture (2013). *Cost Analyses and Benefit Studies for Earthquake-Resistant Construction in Memphis, Tennessee.* NIST GCR 14-917-26. National Institute of Standards and Technology, Gaithersburg, MD, 249 pp.

Networx (2011). *How Much Does a Permanent Wheelchair Ramp Cost?* http://www.networx.com/article/wheelchair-ramp-cost. [accessed December 6, 2017].

Newnan, D.G. (1983). *Engineering Economic Analysis, 2nd Edition.* Engineering Press, Inc., San Jose, CA, 520 p.

Newnan, D.G., Whittaker, J., Eschenbach, T.G., and Lavelle, J.P. (2006). Engineering Economic Analysis, Canadian Edition. Oxford University Press canada, Don Mills, Ontario, 600 p.

NIST (1995). *Recommended Performance-Based Criteria for the Design of Manufactured Home Foundation Systems to Resist Wind and Seismic Loads*. http://fire.nist.gov/bfrlpubs/build95/PDF/b95084.pdf.

NIST (2015). *Seismic Design of Steel Buckling-Restrained Braced Frames: A Guide for Practicing Engineers*, GCR 15-917-34, NEHRP Seismic Design Technical Brief No. 11, produced by the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering for the National Institute of Standards and Technology, Gaithersburg, MD. http://nvlpubs.nist.gov/nistpubs/gcr/2015/NIST.GCR.15-917-34.pdf [accessed 17 October 2017].

(NOAA GFDL) National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory (2016) *Global Warming and Hurricanes An Overview of Current Research Results*. https://www.gfdl.noaa.gov/global-warming-and-hurricanes/ [last accessed 3 February 2017].

(NOAA NHC) National Oceanic and Atmospheric Administration, National Hurricane Center. *Storm Surge Maximum of the Maximum.* Retrieved 2014 from http://www.nhc.noaa.gov/surge/momOverview.php.

(NOAA NWS) National Oceanic and Atmospheric Administration National Weather Service (2017). *Storm Events Database*. https://www.ncdc.noaa.gov/stormevents/ftp.jsp.

(NOAA) National Oceanic and Atmospheric Administration. (2017a) *Sea Level Rise Data*. Retrieved May 2017 from https://coast.noaa.gov/slrdata/.

(NOAA) National Oceanic and Atmospheric Administration. (2017b) *Billion-Dollar Weather and Climate Disasters: Table of Events*. https://www.ncdc.noaa.gov/billions/events/US/1980-2017. [accessed 21 December 2017].

O'Connor, J., (2004). Survey on actual service lives for North American buildings. *Proc. Woodframe Housing Durability and Disaster Issues Conference*, *Las Vegas*, *NV October 2004*, http://cwc.ca/wp-content/uploads/2013/12/DurabilityService_Life_E.pdf. [accessed 16 Mar 2017].

(OECD) "SF1.1 Family Size and Composition," in *OECD Family Database*. http://www.oecd.org/els/family/SF_1_1_Family_size_and_composition.pdf. [accessed 5 December 2017].

Oklahoma Uniform Building Code Commission (2016). *Rules 748 - Uniform Building Code Commission, Adopted Codes, International Residential Code®, 2015 Edition (IRC®, 2015), 748:20-5-1 through 748:20-5-28*. https://www.ok.gov/oubcc/documents/Permanent%20Rule%20IRC%202015.pdf [viewed 14 November 2016].

Olshansky, R.B., Bancroft, R., and Glick, C. (1998): *Promoting the Adoption and Enforcement of Seismic Building Codes: a Guidebook for State Earthquake and Mitigation Managers. FEMA 313*. Federal Emergency Management Agency, Washington, DC, 211 p.

(OMB) Office of Management and Budget (2003). *Circular A-4*.

Orsi, M.J., and Santos, J.R. (2010). Probabilistic modeling of workforce-based disruptions and input-output analysis of interdependent ripple effects. *Economic Systems Research*, *22*, 3-18.

(OSM) OpenStreetMap (2017). *OpenStreetMap Building Footprints*. Retrieved May 2017 from https://www.openstreetmap.org.

Pagni, P.J., and Woycheese, J.P., (2000). Fire spread by brand spotting. In Bryner, S.L., ed. *U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 15th Joint Panel Meeting. Volume 2. Proceedings, San Antonio, TX.* p. 373-380.

Park, C.S., Kim, G., and Choi, S. (2007). Engineering economics. Pearson Prentice Hall, New Jersey.

Perrings, C. (2001). Resilience and sustainability. In H. Folmer, H.L. Gabel, S. Gerking, A. Rose (Eds.), *Frontiers of Environmental Economics*. Cheltenham, pp. 319–41. U.K.: Edward Elgar.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Yuehua, Rezaeian, Sanaz, Harmsen, S.C., Boyd, O.S., Field, Ned, Chen, Rui, Rukstales, K.S., Luco, Nico, Wheeler, R.L., Williams, R.A., and Olsen, A.H. (2014). Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091, 243 p., http://dx.doi.org/10.3133/ofr20141091.

Porter, K. (2017). *A Beginner's Guide to Fragility, Vulnerability, and Risk.* SPA Risk LLC and University of Colorado Boulder, 95 pp., http://www.sparisk.com/pubs/Porter-beginners-guide.pdf.

Porter, K.A. (2000). *Assembly-Based Vulnerability of Buildings and its Uses in Seismic Performance Evaluation and Risk-Management Decision-Making*, Doctoral Dissertation, Stanford University, Stanford, CA, ProQuest Co., Ann Arbor, MI, pub. 99-95274, 196 pp., http://wwwlib.umi.com/dissertations/preview/9995274.

Porter, K.A. (2003). An overview of PEER's performance-based earthquake engineering methodology. *Proc. Ninth International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP9) July 6-9, 2003, San Francisco, CA.* Civil Engineering Risk and Reliability Association (CERRA), http://spot.colorado.edu/~porterka/.

Porter, K.A. (2009a). Cracking an open safe: HAZUS vulnerability functions in terms of structure-independent spectral acceleration. *Earthquake Spectra* 25 (2), 361-378, http://www.sparisk.com/pubs/Porter-2009-Safecrack-Casualty.pdf.

Porter, K.A. (2009b). Cracking an open safe: more HAZUS vulnerability functions in terms of structure-independent spectral acceleration. *Earthquake Spectra* 25 (3), 607-618, http://www.sparisk.com/pubs/Porter-2009-Safecrack-MDF.pdf.

Porter, K.A. (2010). Cracking an open safe: uncertainty in HAZUS-based seismic vulnerability functions. *Earthquake Spectra*, 26 (3), 893-900 http://www.sparisk.com/pubs/Porter-2010-Safecrack-COV.pdf.

Porter, K.A., and K Cobeen (2012). Informing a retrofit ordinance: a soft-story case study. *Proc. 2012 Structures Congress*, Chicago IL, March 29-31, 2012.

Porter, K.A. (2016a). Not safe enough: the case for resilient seismic design. *2016 SEAOC Convention, October 12-15, 2016, Maui HI*, http://www.sparisk.com/pubs/Porter-2016-SEAOC-Resilience.pdf.

Porter, K.A. (2016b). *An Earthquake Urban Search and Rescue Model Illustrated with a Hypothetical Mw 7.0 Earthquake on the Hayward Fault*. Structural Engineering and Structural Mechanics Report SESM 16-03, University of Colorado Boulder, http://www.colorado.edu/ceae/node/1094/attachment.

Porter, K.A., Scawthorn, C.R., and Beck J.L. (2006). Cost-effectiveness of stronger woodframe buildings. *Earthquake Spectra* 22 (1), February 2006, 239-266, DOI:10.1193/1.2162567, http://www.sparisk.com/pubs/Porter-2006-woodframe.pdf.

ProMatcher (2017). *Wheelchair Ramps Costs & Prices – ProMatcher Cost Report*. http://wheelchair-ramps.promatcher.com/cost/. [accessed December 6, 2017].

Quintiere, J.G. (1998). *Principles of Fire Behavior*. Albany, N.Y.: Delmar Publishers.

Ramseyer, C. and Holliday, L. (2014). City of Moore New Building Code for Tornado Resistance. Presentation to the Moore City Council, February 18, 2014. https://www.cityofmoore.com/sites/default/files/main-site/City%20of%20Moore%20Code%20Adoption%20Feb%202014%20-%20Web%20reduced.pdf. [accessed November 8, 2017].

Rashed, T. (2005). Geospatial Technologies, Vulnerability Assessment, and Sustainable Hazards Mitigation in Cities. In M. Campagna, editor, *GIS for Sustainable Development: Bringing Geographic Information Science into Practice towards Sustainability*, Taylor and Francis (CRC Press), New York: 287:309.

Rashed, T. and Weeks, J. (2003). Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas. *International Journal of Geographic Information Science,* 17 (6): 549-576.

Ravetz, J. (2008). State of the stock—What do we know about existing buildings and their future prospects? *Energy Policy*, 36(12), 4462-4470.

Resilient Organisations (2017). *Publications.* http://www.resorgs.org.nz/Publications/books.html. [accessed 30 July 2017].

Resurreccion, J.Z., and Santos, J.R. (2013). Uncertainty modeling of hurricane-based disruptions to interdependent economic and infrastructure systems. *Natural Hazards*, 69, 1497-1518.

Rose, A. (2009). *Economic Resilience to Disasters: Community and Regional Resilience Institute (CARRI) Research Report 8*. Oakridge, TN: CARRI Institute.

Rose, A., and Liao, S. (2005). Modeling regional economic resilience to disasters: A computable general equilibrium analysis of water service disruptions, *Journal of Regional Science*, 45, 75-112.

Rose, A., and Miernyk W. (1989). Input–output analysis: the first fifty years. *Economic Systems Research*, 1, 229-272.

Rose, A., Porter, K.A., Dash, N., Bouabid, J., Huyck, C., Whitehead, J.C., Shaw, D., Eguchi, R. T., Taylor, C.E., McLane, T.R., Tobin, L.T., Ganderton, P.T., Godschalk, D., Kiremidjian, A.S., Tierney, K., and West, C.T. (2007). Benefit-cost analysis of FEMA hazard mitigation grants. *Natural Hazards Review*, 8 (4), 97-111.

RSMeans (2015). *RSMeans Square Foot Costs 2016 37th Edition*, The Gordian Group, Greenville SC, 500 p.

RSMeans (n.d.). *How to Use the City Cost Indexes*. https://www.rsmeansonline.com/References/CCI/2-Assemblies%20(UniFormat)/0-How%20To%20Use.pdf.

Sabelli, R., Mahin, S., and Chang, C. (2003). Seismic demands on steel braced frame buildings with buckling-restrained braces. *Engineering Structures*, 25 (5), 655-666.

Santato, S., Bender, S., and Schaller, M. (2013). *The European Floods Directive and Opportunities offered by Land Use Planning* (CSC Report 12). Climate Service Center, Germany, 75 p.

Santos, J.R. (2006). Inoperability input-output modeling of disruptions to interdependent economic systems. *Systems Engineering*, 9, 20-34.

Santos, J.R., and Haimes, Y.Y. (2004). Modeling the demand reduction input-output inoperability due to terrorism of interconnected infrastructures. *Risk Analysis*, *24*, 1437-1451.

Santos, J.R., Barker, K., and Zelinke, P. (2008). Sequential decision-making in interdependent sectors with multiobjective inoperability decision trees. *Economic Systems Research*, 20, 29-56.

Santos, J.R., Haimes, Y.Y., and Lian (2007). A framework for linking cyber security metrics to the modeling of macroeconomic interdependencies. *Risk Analysis: An International Journal*, 27, 1283-1297.

(SBA) Small Business Administration (2012-2016) *SBA Disaster Loan Data FYs 2012 to 2016*, https://www.sba.gov/loans-grants/see-what-sba-offers/sba-loan-programs/disaster-loans/disaster-loan-data [accessed 4 September 2017].

Scawthorn, C. (2011). *Water Supply in Regards to Fire Following Earthquakes*: 173. Berkeley: Pacific Earthquake Engineering Research Center, College of Engineering, University of California, sponsored by the California Seismic Safety Commission, available at http://www.seismic.ca.gov/pub/CSSC_2011-02_WaterSupply_PEER.pdf with summary at http://peer.berkeley.edu/publications/peer_reports/reports_2011/Fire%20Following%20Earthquake-online-view-layout-sm.pdf.

Schoennagel, T., Balch, J. K., Brenkert-Smith, H., Dennison, P. E., Harvey, B. J., Krawchuk, M. A., Mietkiewicz, N., Morgan, P., Moritz, M. A., Rasker, R., Turner, M. G., and Whitlock, C. 2017. Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences (USA)*, 114 (18): 4582–4590.

Scott, J.H., Thompson, M.P., and Calkin, D.E. (2013). *A Wildfire Risk Assessment Framework for Land and Resource Management.* United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, 83 p.

Seligson, H.A., and Shoaf, K.I. (2003). Human impacts of earthquakes. *Earthquake Engineering Handbook*, W.F. Chen and C.R. Scawthorn, eds., Chapter 28, CRC Press, New York, NY.

Short, K.C., Finney, M.A., Scott, J.H., Gilbertson-Day, J.W., and Grenfell, I.C. (2016). *Spatial Dataset of Probabilistic Wildfire Risk Components for the Conterminous United States*, available at https://doi.org/10.2737/RDS-2016-0034. Edited by U.S. Forest Service. Fort Collins, CO.

Shreve, C.M. and Kellman, I. (2014). Does mitigation save? Reviewing cost-benefit analyses of disaster risk reduction, *International Journal of Disaster Risk Reduction*, 10, 213-235.

Simmons, K.M., Kovacs, P., and Kopp, G.A. (2015). Tornado damage mitigation: Benefit–cost analysis of enhanced building codes in Oklahoma. *Weather, Climate, and Society* 7 (2), 169-178.

Southern Building Code Congress International (1946). *Southern Standard Building Code*. Birmingham AL: Southern Building Code Congress International.

Spence, R. (2004). Risk and regulation: can improved government action reduce the impacts of natural disasters? *Building Research and Information*, 32 (5), 391-402.

Suzuki, S., Manzello, S.L., Lage, M., and Laing, G. 2012. Firebrand generation data obtained from a full-scale structure burn. *Intl. J. Wildland Fire*, 21, 961-968.

Sweet, W.V., Kopp, R.E., Weaver, C.P., Obeyskera, J., Horton, R.M., Thieler, E.R., and Zervas, C. (2017). *Global and regional sea level rise scenarios for the United States*. Silver Spring, MD. https://repository.library.noaa.gov/view/noaa/14344.

Tate, E., Muñoz, C., and Suchan, J. (2015). Uncertainty and Sensitivity Analysis of the HAZUS-MH Flood Model, *Natural Hazards Review*, 16 (3).

(TCLEE) Technical Council for Lifeline Earthquake Engineering (2005). *Fire Following Earthquake*. Reston: American Society of Civil Engineers.

Thomas, D.S.K., Phillips, B.D., Lovekamp, W.E., and Fothergill A., eds (2013). *Social Vulnerability to Disasters*. CRC Press: Boca Raton.

Thompson, M.P., Calkin, D.E., Finney, M.A., Ager, A.A., and Gilbertson-Day, J.W. (2011). Integrated national-scale assessment of wildfire risk to human and ecological values. *Stochastic Environmental Research and Risk Assessment*, 25 (6), 761-780.

United States Army Corps of Engineers (2013). *Principles and Guidelines for Federal Investments in Water Resources, Federal Support Toolbox, National Action Plan: Integrated Water Resources Management (IWRM) Actions*. Presentation of Olsen, R. https://acwi.gov/climate_wkg/minutes/acwi-olsen-4-17-13.pdf. [accessed November 8, 2017].

(USACE) U.S. Army Corps of Engineers (2012). *Memorandum: Reissuance of the U.S. Army Corps of Engineers Environmental Operating Principles*. August 7, 2012. http://www.usace.army.mil/Portals/2/docs/Environmental/EAB/eop_coe_reissuedeop_07aug2012.pdf.

(USACE) U.S. Army Corps of Engineers (2016). *Fiscal Year 2016 United States Army Annual Financial Report*. http://www.publications.usace.army.mil/Portals/76/Publications/Miscellaneous/FY2016_USACE-AFR_FINAL11-15v2.pdf.

(USCB) United States Census Bureau (2004). *Census 2000 Data*. https://www.census.gov//census2000/states/us.html. [accessed 22 December 2017].

(USCB) United States Census Bureau (2010a). *Florida 2010 Census – Census Tract Reference Maps*. https://www.census.gov/geo/maps-data/maps/2010ref/st12_tract.html.

(USCB) United States Census Bureau (2010b). *2010 Characteristics of New Housing*. https://www.census.gov/construction/chars/pdf/c25ann2010.pdf. Page 389.

(USCB) United States Census Bureau (2010-2004). *American Community Survey (ACS) 5 Year Estimates*.

(USCB) United State Census Bureau (2012). *Manufacturing and International Trade Report: 2012*. https://www.census.gov/foreign-trade/Press-Release/MITR/2012/index.html. [accessed December 6, 2017].

(USCB) United States Census Bureau (2017). *Population and Housing Unit Estimates*. https://www.census.gov/programs-surveys/popest/data/tables.All.html.

United States Department of Commerce (1997). *Regional Multipliers: A User Handbook for the Regional Input-Output Modeling System*, Washington, DC: U.S. Government Printing Office.

(USGS) United States Geological Survey (2017). *National Elevation Dataset*. Retrieved May 2017 from https://lta.cr.usgs.gov/NED.

Varney, T.K. (2016). 2016's top business risks: business interruption remains top spot fourth year in a row. *Supply and Demand Chain Executive: Risk Management*. http://www.sdcexec.com/article/12165269/2016s-top-business-risks-business-interruption-remains-top-spot-fourth-year-in-a-row. [accessed 31 Jul 2017].

Vickery, P.J. and Skerlj, P.F. (2005). Hurricane gust factors revisited. *Journal of Structural Engineering*, *131* (5), 825-832.

Watkins, T. (n.d.). *An Introduction to Cost Benefit Analysis*. http://www.sjsu.edu/faculty/watkins/cba.htm. [accessed December 6, 2017].

Webb G., Tierney K., and Dahlhamer J. (2000). Business and disasters: empirical patterns and unanswered questions. *Natural Hazards Review*, *1*, 83-90.

Webster, P. J., Holland, G. J., Curry, J. A., and Chang, H.-R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*. 309: 1844-1846.

White House (2016). *Standards and Finance to Support Community Resilience*, Washington, DC, 29 p.

Wills, C.J. and Clahan, K.B. (2006). Developing a map of geologically defined site-conditions categories for California. *Bulletin of the Seismological Society of America*, *96* (4A), 1483-1501

World Bank (2017). *Population Growth (Annual %)*. https://data.worldbank.org/indicator/SP.POP.GROW?locations=US&name_desc=true. [accessed 6 December 2017].

Wright, R., Mitigation Directorate, & United States House of Representatives (2014). *A Review of the National Earthquake Hazards Reduction Program* (NEHRP). https://dam-production.s3-us-gov-west-1.amazonaws.com/uploads/1408038637998-3354eb12e21447bc19f59d80a75a82fa/7-29-14%20-%20NEHRP_508.pdf [accessed 19 October 2017].

Zhuang, J., Liang, Z., Lin, T., and De Guzman, F. (2007). *Theory and Practice in the Choice of Social Discount Rate for Cost-Benefit Analysis: a Survey.*

Appendix A. Glossary and List of Acronyms

A.1 Glossary

BCR	Benefit-cost ratio, the ratio of the benefits of a project or proposal, expressed in monetary terms, relative to its costs, also expressed in monetary terms. Calculated as the discounted value of incremental benefits divided by the discounted value of incremental costs.
Defensible space	An area either natural or manmade, where material capable of allowing a fire to spread unchecked has been treated, cleared or modified to slow the rate and intensity of an advancing wildfire and to create an area for fire suppression operations to occur.
Fragility function	A curve in x-y space where x measures environmental excitation, y measures the occurrence probability of some undesirable outcome, and the curve represents the performance of a specified asset class.
Fragility	The relationship between environmental excitation and the occurrence probability of some undesirable outcome, such as the collapse of a building.
Hazard curve	An x-y chart where x measures excitation (e.g., wind speed) and y measures exceedance frequency (e.g., times per year). A curve in that space represents hazard for a given site. It is generally higher on the left and lower on the right.
Hazard	Here, the mathematical relationship between a (usually scalar) measure of environmental excitation (such as wind speed) and the frequency with which that level of excitation is exceeded, e.g., in times per year.
Ignition-resistant construction and materials	A schedule of additional requirements for construction in wildland-urban interface areas based on extreme (Class 1); high (Class 2), and moderate (Class 3), fire hazard. Ignition resistant building materials resist ignition or sustained flaming combustion sufficiently so as to reduce losses from wildland-urban interface conflagrations under worst-case weather and fuel conditions with wildfire exposure of burning embers and small flames, as prescribed in Section 503 of the 2015 IWUIC.
Interface	Areas with ≥6.18 houses per km^2 and <50 percent cover of vegetation located <2.4 km of an area ≥5 km^2 in size that is ≥75 percent vegetated.

Intermix Areas with ≥6.18 houses per km^2 and ≥50 percent cover of wildland vegetation.

Risk curve An x-y chart where x measures loss (e.g., deaths) and y measures exceedance frequency (e.g., times per year). A curve in that space represents risk for a given asset. It is generally higher on the left and lower on the right.

Risk Here, the mathematical relationship between a (usually scalar) measure of loss (such as number of people killed) and the frequency with which that level of loss is exceeded, e.g., in times per year.

Vulnerability function A curve in x-y space where x measures environmental excitation, y measures the expected value of loss, and the curve represents the performance of a specified asset class, such as a woodframe single-family dwelling built after 2012.

Vulnerability The relationship between a scalar measure of environmental excitation (e.g., momentum flux in the case of flooding in a velocity zone—a stream or seashore) and a scalar degree of loss (e.g., repair cost as a fraction of replacement cost, new).

Vulnerable (socially) Vulnerability is also used throughout the Interim Study to represent socially vulnerable populations. Social vulnerability refers to the characteristics of people and groups that influence their ability to anticipate, cope with, resist and recover from the impact of disasters. These characteristics may be social, economic, physical or environmental and are influenced by the structural conditions within society that affect the ability to garner resources related to hazards and disasters.

Wildland An area in which development is essentially nonexistent, except for roads, railroads, power lines and similar facilities.

W**ildland-urban interface** The geographical area where structures and other human development meets or intermingles with wildland or vegetative fuels.

A.2 List of Acronyms

AAL	Average Annualized Loss
ACS	American Community Surveys
ADA	Americans with Disabilities Act of 1990
AIA	American Institute of Architects
AIS	Abbreviated Injury Scale
ALE	Additional Living Expenses
ASCE	American Society of Civil Engineers
ASFPM	Association of State Floodplain Managers
BCEGS	Building Code Effectiveness Grading Schedule
BCP	Business Continuity Planning
BCR	Benefit-Cost Ratio
BEA	Bureau of Economic Analysis
BFE	Base Flood Elevation
BI	Business Interruption
BP	Burn Probability
CalTech	California Institute of Technology
CDBG	Community Development Block Grant
CEUS	Central and Eastern United States
CFIRE	Council on Finance, Insurance and Real Estate
CGE	Computable General Equilibrium
CPI	Consumer Price Index
CRS	Community Rating System
CUREE	Consortium of Universities for Research in Earthquake Engineering
DIIM	Dynamic Interoperabilty IO Model
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DR	Disaster Recovery
ERM	Enterprise Risk Management
EAL	Expected Annualized Loss
EDA	U.S. Economic Development Administration
EIA	Energy Information Administration
ETS	Engineered tie-down system
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Studies
FMA	Flood Mitigation Assistance
GBS	General Building Stock
GDP	Gross Domestic Product
GEM	Global Earthquake Model
GIC	Glacier and Ice Cap Mass Balance
GIS	Geographic Information System
GMSL	Global Mean Sea Level
GSL	Global Average Sea Level
HFIAA	Homeowner Flood Insurance Affordability Act

HMA	Hazard Mitigation Assistance
HMGP	Hazard Mitigation Grant Program
HUD	U.S. Department of Housing and Urban Development
IBC	International Building Code
IBHS	Insurance Institute for Business and Home Safety
ICC	International Code Council
IEBC	*International Existing Building Code*
IEMax	Incrementally Efficient Maximum
IFM	Integrated Flood Mitigation
IIM	Inoperability IO Model
IO	Input-Output
IRC	*International Residential Code*
ISO	Insurance Services Office
ISR	Inventory-to-Sales Ratios
IWUIC	*International Wildland-Urban Interface Code*
LSL	Local Sea Level Rise
MCE	Maximum Considered Earthquake
MCE_R	Maximum Considered Earthquake, Risk Adjusted
MMC	Multihazard Mitigation Council
MOM	Maximum-of-Maximum
NAICS	North American Industry Classification System
NEHRP	National Earthquake Hazard Reduction Program
NFIP	National Flood Insurance Program
NFPA	National Fire Protection Association
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
NOAA	National Oceanographic and Atmospheric Administration
NSHMP	National Seismic Hazard Mapping Program
NWS	National Weather Service
O&P	Overhead and Profit
OMB	Office of Management and Budget
OSB	Oriented Strand Board
OSM	OpenStreetMap
PA	Public Assistance
PDM	Pre-Disaster Mitigation
PPP	Purchasing Power Parity
PTSD	Post Traumatic Stress Disorder
RCP	Representative Concentration Pathways
SLR	Sea Level Rise
SBA	Small Business Administration
SEAOC	Structural Engineers Association of California
SEAONC	Structural Engineers Association of Northern California
SEAOSC	Structural Engineers Association of Southern California
SEAOSD	Structural Engineers Association of San Diego
SEC	U.S. Securities and Exchange Commission
SEI	Structural Engineering Institute

SFHA	Special Flood Hazard Area
SRTP	Social Rate of Time Preference
SSHWS	Saffir-Simpson Hurricane Wind Scale
TIPS	Treasury Inflation-Protected Securities
UBC	*Uniform Building Code*
UDF	User-Defined Facilities
URM	Unreinforced Masonry
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VSFA	Value of Statistical Fatality Avoided
WHP	Wildfire Hazard Potential
WUI	Wildland-Urban Interface
WUS	Western United States

Appendix B. Databases

B.1 Building-Related Grants

Program area Y (EDW SAP Data Tools HMGP from NEMIS; FMA & PDM from eGrant)
Project title Y
Project status
Project category, if agency categorizes projects (project type)
Declaration number (when applicable)
Declaration title
Date of loss
Date project approved or awarded (FEMA is still awarding grants 10 years after Katrina)
Date mitigation completed (Y, but sometimes years after the work completed)
Primary peril (flood, wind, earthquake, fire, ...) (Y, but can be dirty)
Peril 2 (if any)
Location: census block or address to nearest say 10 or 100, or latitude and longitude (Y, can be dirty)
Elevation of 1st floor above grade (feet, at main entrance), pre-disaster (iffy; look in BCA)
Original year built (paper files)
Building total floor area (sq ft) (paper files)
Use of the building (occupancy); For businesses: NAICS or SIC (may be able to extrapolate from project type--public or private)
Number of stories above grade (iffy)
Number of basements (Y/N)
Replacement cost (new) of building before disaster (paper files)
Replacement cost (new) of building after disaster and repairs/upgrades (paper files)
Number of employees or residents (no, but nonresidential may be in BCA or paper files)
Drawings or description or Xactimate file (no, but paper files)
Describe any improvement (or just return to pre-disaster condition?) (project description)
FEMA model building type (or wall material) (paper files)
In the case of DR: total verified loss ($) (PA)
Total project cost ($ cost of mitigation or repair) (not to the level of individual buildings; paper)
Grant amount ($) (same)
Loss verification report if any (PA not on mitigation side)

B.2 Data.gov Database of HMGP grants

Field name	Sample
Region	8
State	Utah
disasterNumber	820
declarationDate	1989-01-31T00:00:00 +00:00
incidentType	Flood
disasterTitle	DIKE FAILURE & FLASH FLOODING
projectNumber	2
projectType	600.1: Warning Systems (as a Component of a Planned, Adopted, and Exercised Risk Reduction Plan)
projectTitle	FLOOD DETECTION INSTRUMENTS
projectDescription	INSTALL INSTRUMENTS BASED ON ASSESSMENT OF STRATEGIC LOCATIONS WHERE FLOODING NORMALLY OCCURS TO RECORD WATER AND RIVERFALL LEVELS. INSTRUMENTS TO BE DIRECT-TRANSMITTING TO EMERGENCY OFFICE FOR WARNINGS AND EVACUATION.
projectCounties	WASHINGTON
status	Closed
subgrantee	ST. GEORGE
subgranteeFIPSCode	5365330
projectAmount	80000
costSharePercentage	38
hash	55e80c336c8590edb3c3309d2a61ac90
lastRefresh	2014-11-20T15:16:39 +00:00

Table B-1. Fields from HMGP grants database.

B.3 PA Data Availability

When IBM (2016) documented the design of the Public Assistance (PA) data repository it designed for FEMA, it described several so-called star schemas—descriptions of sets of database tables. At the center of each star is a table of facts, the information the project team cared about, such as a list of PA applicants, each with an associated disaster ID and location ID. Attached to the center of the star are tables listing the allowable values of one field, such as a list of allowable applicant IDs. Each table has a table name and a set of field names. Table B-2 maps the PA data to the 2017 *Mitigation Saves* study data. In the column labeled “PA source,” entries are formatted as table.field, where table refers to the table name in the PA database and field refers to the field name in the PA table.

Field	PA source	Comment
Program area	"PA"	
Project title	PA_PROJECT_SITE_DIMENSIONS.project_location_desc	
Project status		
Project category, if agency categorizes projects (project type)		
Declaration number (when applicable)	PA_CASE_MGMT_PRJTN_FACTS.disaster_id	
Declaration title		
Date of loss		
Date project approved or awarded		
Date mitigation completed		
Primary peril (flood, wind, earthquake, fire, ...)		
Peril 2 (if any)		
Location: census block or address to nearest say 10 or 100, or latitude and longitude	PA_PROJECT_FACTS.LATITUDE & PA_PROJECT_FACTS.LONGITUDE	Separate into two fields
Elevation of 1st floor above grade (feet, at main entrance), pre-disaster		
Original year built		
Building total floor area (sq ft)		
Use of the building (occupancy); For businesses: NAICS or SIC		
Number of stories above grade		
Number of basements		
Replacement cost (new) of building before disaster		
Replacement cost (new) of building after disaster and repairs/upgrades		
Number of employees or residents		
Drawings or description or Xactimate file		
Project description (describe any improvement or just return to pre-disaster condition?)	PA_PROJECT_SITE_DIMENSIONS.SCOPE_OF_WORK	
FEMA model building type (or wall material)		
In the case of DR: total verified loss ($)		
Total project cost ($ cost of mitigation or repair)	PA_PROJECT_FACTS.PROJECT_AMOUNT	
Grant amount ($)	PA_PROJECT_FACTS.FEDERAL_SHARE_OBLIGATED	
Loss verification report if any		

Table B-2. Mapping PA data to 2017 *Mitigation Saves* study data.

B.4 EDA

EDA's electronic data date back to 2000. Fewer than 1,000 records address disaster. EDA provided just the disaster-related data, flagged based on appropriation descriptions (floods, hurricanes, etc.). The data reflect between 30 and 50 grants per year, varying between $100,000 and $2,000,000 in EDA funding. Grants go to nonprofits and public-sector organizations, and deal with sewer lines, road repairs, and general construction (public works).

Appendix C. City of Moore Wind Code Enhancements

Quoted from City of Moore, Oklahoma (2014b):

The following additions are hereby included in the dwelling code for the purposes of establishing minimum regulations governing residential construction for high wind resistance:

1. Roof sheathing (OSB or plywood) shall be nailed with 8d ring shank (0.131" × 2.5") or 10d (0.148" × 3") nails on 4" on center along the edges and 6" on center in the field. Dimensional lumber decking is not allowed.
2. Maximum spacing for roof framing shall be 16 inches on center. Minimum nominal sheathing panel size shall be 7/16. Minimum wood structural panel span rating shall be 24/16.
3. Connections for roof framing shall be designed for both compression and tension, and may include nail plates or steel connection plates. Connections for roof framing shall include connections on rafters, web members, purlins, kickers, bracing connections, and the connections to interior brace wall top plates or ceiling joists.
4. Gable end walls shall be tied to the structure, and may include steel connection plates or straps. The connections shall be made at the top and bottom of the gable end wall.
5. Structural sheathing panel (OSB or plywood) shall be required for gable end walls.
6. Hurricane clip or framing anchor shall be required on all rafter to wall connections.
7. The upper and lower story wall sheathing shall be nailed to the common rim board.
8. All walls shall be continuously sheathed with structural sheathing (OSB or plywood) using the CS-WSP method. Garage doors shall be framed using the sheathed portal frame method CS-PF. No form of intermittent bracing shall be allowed on an outer wall. Intermittent bracing may only be used for interior braced wall lines.
9. Nailing of wall sheathing (OSB or plywood) shall be increased to 8d ring shank (0.131" × 2.5") or 10d (0.148" × 3") nails on 4" on center along the edges and 6" on center in the field.
10. Structural wood sheathing shall be extended to lap the sill plate and nailed to the sill plate using a 4" on center along the edges. Structural wood sheathing shall be nailed to rim board if present with 8d ring shank (0.131 × 2.5") or 10d (0.148" × 3") nails on 4" on center along both the top and bottom edges of the rim board.
11. Garage doors shall be rated to 135 mph wind or above.
12. Exterior wall studs shall be 16" on center.

Appendix D. Which Years to Include for BCA of PA Grants

PA grants changed substantially after Hurricane Katrina struck in 2005. During the course of the study, the project team realized that those changes could influence the project objectives and affect the analysis. At least three options presented themselves, summarized in Table D-1. In light of their advantages and disadvantages, the project team selected option B.

Option	Advantages	Disadvantages
A. Estimate BCR since 1993	Consistent with the 2005 *Mitigation Saves* study and with proposal	Data-quality issues; less useful to readers
B. Estimate BCR from new mitigation	Much more useful to readers; better data quality	Less consistent with proposal
C. Do both	Advantages of both A and B	Inconsistent data and more work, without providing a compelling benefit to the reader

Table D-1. Options for how to deal with changes in PA grants after 2005.

Appendix E. Innovations Since the 2005 Mitigation Saves Study

Inventory of U.S. building stock. The project team used a new (2008) building-stock inventory extracted from Hazus, but updated to 2016, that considered population growth (from Census Bureau data) and construction-cost inflation (from the leading publisher of U.S. construction costs, RSMeans). The 2005 *Mitigation Saves* study had no such inventory.

Seismic vulnerability for buildings designed to exceed I-Code requirements. The project team created new vulnerability functions for repair costs, casualties, and loss of function (dollars, deaths, and downtime) for the entire U.S. building stock using the Cracking an Open Safe method (Porter 2009b). The 2005 *Mitigation Saves* study did not consider designing to exceed I-Code requirements. The net effect is to provide support for a new, practical, low-cost mitigation option.

Seismic impairment of buildings designed to exceed I-Code requirements. The project team evaluated earthquake-induced building impairment (collapse, red-tag, and yellow-tag) using two new seismic fragility functions developed for the USGS (Porter 2016). These rely solely on three authoritative sources: (1) Luco et al.'s (2007) fragility model underlying ASCE 7-10 risk-targeted maximum considered earthquake (MCE_R) map, (2) FEMA P-695 (FEMA 2009) best estimate of the collapse probability of new, code-compliant buildings at MCE shaking, and (3) observations of the relative number of collapsed, red-tagged, and yellow-tagged buildings in the 1989 Loma Prieta, 1994 Northridge, and 2014 South Napa Earthquakes. The model has been published in a leading scholarly journal (*Earthquake Spectra*) and extensively peer reviewed for the USGS, both by USGS scientists and by respected members of the Structural Engineers Association of Northern California. It had been presented to hundreds of members of Structural Engineers Association of Northern California (SEAONC), Structural Engineers Association of Southern California (SEAOSC), Structural Engineers Association of San Diego (SEAOSD), and Structural Engineers Association of California (SEAOC), as well as faculty and graduate students of several leading universities. The 2005 *Mitigation Saves* study did not consider impairment, red-tagging or yellow-tagging. The net effect is a more robust depiction of risk because it includes this more-tangible performance metric and support for a new, practical, low-cost mitigation option.

Sea level rise. Weather-related losses in the 2017 study account for LSL. The 2005 *Mitigation Saves* study did not consider changing sea levels. The net effect is a more accurate picture of mitigation savings from flood mitigation.

Mitigation investments by HUD and EDA. The project team expanded the scope of federal mitigation investments to include grants from programs outside HMGP, PDMA, and Project Impact. The 2005 *Mitigation Saves* study did not include these. The net effect is a richer depiction of the benefit of public-sector mitigation investment.

Mental-health disaster impacts. The project team accounted for the psychological trauma that disasters produce with a new methodology. The 2005 *Mitigation Saves* study did not address mental health. The net effect is a richer depiction of disaster losses, more consistent with Clinton's (1994) executive order to consider all types of benefits, tangible and intangible, from infrastructure investment. This addition raises BCRs and makes them more accurate.

Mitigation synergies. Few mitigation projects focus solely on one type of peril. Even when they do, the potential exists for externalities or spillovers. This project offers a framework to quantify synergies between mitigation strategies, such as between building design to exceed I-Code requirements, structural and nonstructural retrofit of existing buildings, and BCP and DR. An organization that engages in enterprise risk management (ERM) using all three strategies is likely to be more resilient than one that engages in only one or two. Its risk of ruin seems likely to be more reduced by such a comprehensive ERM approach than the sum of their individual effects would indicate.

Appendix F. Sea Level Rise

To estimate the benefits of coastal flood mitigation, one must quantify LSL. The analysis requires baseline, lower-bound, and upper-bound values of LSL over time to estimate BCRs and to test sensitivity to uncertainty. The project team considered the advantages and disadvantages of three reasonable options:

1. Kopp (2014) provides analysis and a spreadsheet estimating LSL at various coastal locations by decade under each of three emissions pathways.
2. NOAA (2017a) lays out global mean sea level rise (GMSL) under each of 6 scenarios (labeled low, intermediate low, through extreme). NOAA (2017a) provides GMSL data on a 1-degree grid.
3. A combination of the two.

Sea Level Rise Option 1: Kopp (2014)

Advantages:

1. Provides best estimates of LSL by location and decade under each of several emissions pathways.
2. Nobody knows what emissions pathway will turn out to be closest to the truth, but it is straightforward to condition on them, e.g., to say "Our baseline BCRs assume RCP6. Our lower-bound BCRs assume RCP8.5. Our upper-bound BCRs assume RCP 2.6." One can call this advantage "clear probabilistic conditioning."
3. Authoritative.

Disadvantages:

1. Not the newest, latest, greatest technique.
2. Not aligned with Union of Concerned Scientists.
3. Spatial data requires difficult spatial interpolation.

Sea Level Rise Option 2: NOAA (2017a)

Advantages:

1. Best estimates of GMSL by 1-degree grid cell and decade.
2. Practical to implement.
3. Latest, greatest.
4. Aligned with Union of Concerned Scientists.
5. Authoritative.

Disadvantages:

1. Scenario labels low, moderate-low... extreme are misleading. They imply, for example, that moderate is some sort of best estimate of future GMSL. Closer inspection suggests however that it is nothing of the kind—not some sort of probabilistic mean, but rather it is labeled moderate only because it is an intermediate value in the range the authors considered valid.

2. BCA must attempt to provide best-estimate values, so disadvantage 1 makes NOAA (2017a) largely useless unless one can tie its scenarios back to clear probabilistic conditioning.
3. Scenario selection guidance in Section 6.1 is of little help for BCA.

Sea Level Rise Option 3: Combine Kopp (2014) and NOAA (2017a)

Description: select the NOAA (2017a) scenarios that most closely resemble the project team's preferred Kopp (2014) baseline, lower-bound, and upper-bound emissions pathways, namely:

- Baseline = mean outcomes of RCP6.0 (virtually identical to RCP4.5). Closest to intermediate-low.
- Lower bound = high exceedance probability under RCP2.6. Closest to low.
- Upper bound = low exceedance probability under RCP8.5. Closest to intermediate-high.

Advantages:

1. Practical data set: best estimates of GMSL by 1-degree grid cell and decade.
2. Latest, greatest.
3. Aligned with Union of Concerned Scientists.
4. Authoritative.
5. Clear probabilistic conditioning.
6. Baseline errs on conservative side, a key requirement of the project team's Interim Study.

Disadvantages:

1. None are obvious.

With the advice of the oversight committee and FEMA, the project team selected option 3, combine Kopp (2014) and NOAA (2017a).

This appendix deals with whether and how to consider sea level rise (SLR) and future changes in precipitation and wind hazard. The project team used the recent and widely cited estimates of LSL rise offered by Kopp et al. (2014). Their estimates account for land water storage, Greenland ice sheet melt, Antarctic ice sheet melt, glacier and ice cap mass balance, oceanographic processes (thermal expansion and regional effects), and the non-climatic background. At a global level, assuming greenhouse gas emissions continue to increase throughout the 21st century (the Representative Concentration Pathways, RCP, trajectory 8.5), Kopp et al. estimate a likely global average sea level (GSL) rise "of 0.6–1.0 m by 2100, with a very likely range of 0.5–1.2 m and a virtually certain (99% probability) range of 0.4–1.8 m." See Kopp et al.'s (2014) Table 1 for a summary of their findings.

Kopp et al.'s upper limit of 1.8m is consistent with the 95th percentile estimated by Jevreja et al. (2014). Kopp et al.'s "likely" range expresses the average value ± one standard deviation (oversimplifying slightly). Their very-likely range spans the mean ± 1.6 standard deviations. Their virtual-certainty range spans the mean ± 2.6 standard deviations.

Like other authors, Kopp et al. offer lower estimates of GSL for scenarios where greenhouse gas emissions peak in the 21st century, then decline: RCP 2.6 estimates GSL if emissions peak in the present decade and then decline; RCP 4.5 assumes emissions peak in 2040; and RCP 6 in 2080.

Despite the uncertainties in each RCP and the uncertainty about when the world will effectively cause emissions to decline (e.g., the choice between RCPs), the range in GSL is reasonably constrained: the mean values are 2.9 feet under a continuously increasing emissions pathway (RCP 8.5), 2.0 feet under a middle-of-the-road pathway (RCP 4.5), and 1.8 feet under the most optimistic pathway (RCP 2.6). Even within an assumption of an emissions pathway, the year-2100 GSL under each RCP is somewhat uncertain, but the range is not very large: on the order of ± 30%. The project team would consider an order of magnitude to represent a large degree of uncertainty; plus, or minus 30% would be considered a fairly well constrained range for many common structural engineering problems, such as the fundamental period of vibration of a building. The point is that despite various uncertainties, the overall range of possible global sea level rise is fairly well constrained.

To return to the Kopp et al. (2014) estimates of LSL rise relative to 2000 levels in 2030, 2050, 2100, and beyond: their curves estimate LSL at 24 cities along the entire Atlantic, Gulf, and Pacific U.S. Coasts. If one thinks of the winners in LSL as places where sea level stays the same or decreases, and the losers as places where sea level increases, then Alaska is the big winner (LSL dropping as much as 3.5 feet by 2100), while the biggest losers are spread along the entire Atlantic and Gulf U.S. Coasts, with likely LSL rises up to 4 feet or more and 95th percentiles as high as 6.5 feet by 2100.

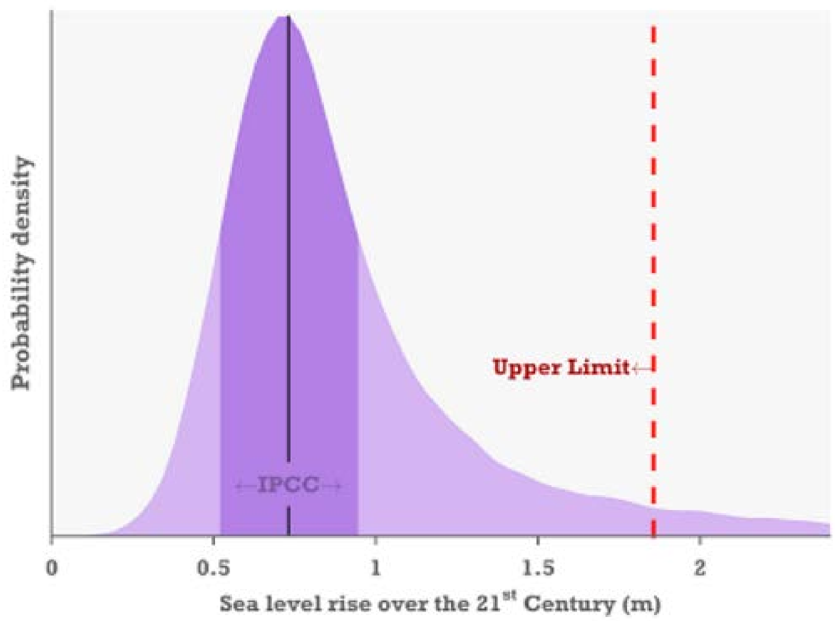
BCA has to consider uncertainty, but it is really about average values. The project team's goal is therefore to provide best estimates of BCR, not best or worst cases, so the tails of LSL are of less interest here than mean values. The project team therefore considers the mean values of RCP 6 as the baseline emissions trajectory. The project later tests sensitivity of BCR to LSL using two extremes: a lower-bound LSL (5th percentile) of the most optimistic emissions trajectory (RCP 2.6) and an upper-bound LSL (95th percentile) of the most pessimistic trajectory (RCP 8.5). See Chapter 3 for ranges. For example, the lower-bound, mean, and upper-bound year-2100 LSL for New York City are 0.9, 2.5, and 5.1 feet, respectively. The values for Miami, FL, are similar: 0.9, 2.2, and 4.3 feet. For San Diego, CA, they are 0.9, 2.1, and 4.1 feet.

For the reader who is interested in worst cases, LSL becomes more catastrophic farther into the future under RCP 8.5: LSL of 12.4-feet in Charleston, South Carolina by the year 2200 means that the city, in which the highest elevation is approximately 14-feet, ceases to exist in its present location by the end of the next century.

Kopp et al. (2014) estimate of the contribution to global sea level (GSL) rise in centimeters under three assumptions of how well humanity controls greenhouse gases (called Representative Concentration Pathways, RCP). See Table F-1. Column headers 50, 17-83, etc., refer to percentiles. Components refer to the contribution to GSL from several sources: glacier and ice cap mass balance (GIC), Greenland ice sheet melt (GIS), Antarctic ice sheet melt (AIS), thermal expansion and regional effects (TE), and land water storage (LWS).

cm	RCP 8.5					RCP 4.5					RCP 2.6				
	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5	99.9
2100—Components															
GIC	18	14–21	11–24	7–29	<30	13	10–17	7–19	3–23	<25	12	9–15	7–17	3–20	<25
GIS	14	8–25	5–39	3–70	<95	9	4–15	2–23	0–40	<55	6	4–12	3–17	2–31	<45
AIS	4	−8 to 15	−11 to 33	−14 to 91	<155	5	−5 to 16	−9 to 33	−11 to 88	<150	6	−4 to 17	−8 to 35	−10 to 93	<155
TE	37	28–46	22–52	12–62	<65	26	18–34	13–40	4–48	<55	19	13–26	8–31	1–38	<40
LWS	5	3–7	2–8	−0 to 11	<11	5	3–7	2–8	−0 to 11	<11	5	3–7	2–8	−0 to 11	<11
Total	79	62–100	52–121	39–176	<245	59	45–77	36–93	24–147	<215	50	37–65	29–82	19–141	<210
Projections by year															
2030	14	12–17	11–18	8–21	<25	14	12–16	10–18	8–20	<20	14	12–16	10–18	8–20	<20
2050	29	24–34	21–38	16–49	<60	26	21–31	18–35	14–44	<55	25	21–29	18–33	14–43	<55
2100	79	62–100	52–121	39–176	<245	59	45–77	36–93	24–147	<215	50	37–65	29–82	19–141	<210
2150	130	100–180	80–230	60–370	<540	90	60–130	40–170	20–310	<480	70	50–110	30–150	20–290	<460
2200	200	130–280	100–370	60–630	<950	130	70–200	40–270	10–520	<830	100	50–160	30–240	10–500	<810

Table F-1. Global sea- level rise projections.



Note: Their 1.8-meter upper limit (95th percentile) is about the same as the 99th percentile of Kopp et al. (2014), which only means that Jevreja et al. express a so somewhat more pessimistic worst case than Kopp et al., not that they substantially disagree.

Figure F-1. Jevreja et al. (2014)'s estimated probability distribution function of GSL by the year 2100.

Location	Year	Lower	Baseline	Upper
Portland, ME	2030	0.2	0.6	0.9
	2050	0.3	1.0	1.7
	2100	0.4	2.1	4.6
Boston, MA	2030	0.3	0.6	1
	2050	0.4	1.1	1.8
	2100	0.7	2.3	4.9
Newport, RI	2030	0.3	0.7	1.1
	2050	0.5	1.2	1.9
	2100	0.8	2.4	5
New York, NY	2030	0.3	0.7	1.2
	2050	0.5	1.2	1.9
	2100	0.9	2.5	5.1
Atlantic City, NJ	2030	0.4	0.8	1.1
	2050	0.7	1.3	2
	2100	1.2	2.8	5.3
Philadelphia, PA	2030	0.3	0.7	1.1
	2050	0.5	1.2	1.9
	2100	0.9	2.5	5
Lewes, DE	2030	0.4	0.7	1.1
	2050	0.7	1.2	1.9
	2100	1.1	2.7	5
Baltimore, MD	2030	0.3	0.7	1
	2050	0.6	1.2	1.8
	2100	1.0	2.5	4.9
Washington, DC	2030	0.3	0.7	1
	2050	0.6	1.2	1.8
	2100	1.0	2.5	4.8
Norfolk, VA	2030	0.5	0.8	1.1
	2050	0.8	1.4	2
	2100	1.4	2.9	5.2
Wilmington, NC	2030	0.3	0.6	0.9
	2050	0.5	1.0	1.6
	2100	0.8	2.2	4.3
Charleston, SC	2030	0.4	0.7	0.9
	2050	0.7	1.1	1.6
	2100	1.0	2.4	4.5
Fort Pulaski, GA	2030	0.4	0.7	0.9
	2050	0.7	1.1	1.7
	2100	1.1	2.4	4.6
Miami, FL	2030	0.3	0.6	0.9
	2050	0.6	1.0	1.5
	2100	0.9	2.2	4.3
Pensacola, FL	2030	0.2	0.5	0.8
	2050	0.5	0.9	1.5
	2100	0.7	2.1	4.2

Location	Year	Lower	Baseline	Upper
Grand Isle, LA	2030	0.9	1.2	1.5
	2050	1.6	2.1	2.6
	2100	3.0	4.4	6.5
Galveston, TX	2030	0.7	1.0	1.2
	2050	1.2	1.6	2.2
	2100	2.1	3.5	5.7
San Diego, CA	2030	0.3	0.5	0.6
	2050	0.5	0.9	1.3
	2100	0.9	2.1	4.1
San Francisco, CA	2030	0.3	0.4	0.6
	2050	0.4	0.8	1.3
	2100	0.8	2.0	4
Astoria, OR	2030	0.0	0.2	0.3
	2050	0.0	0.4	0.8
	2100	0.0	1.1	3
Seattle, WA	2030	0.2	0.4	0.5
	2050	0.4	0.8	1.1
	2100	0.7	1.9	3.7
Juneau, AK	2030	-1.3	-1.2	-1
	2050	-2.2	-1.9	-1.5
	2100	-4.4	-3.4	-1.7
Anchorage, AK	2030	-0.2	0.2	0.4
	2050	-0.4	0.2	0.8
	2100	-0.6	0.5	2
Honolulu, HI	2030	0.3	0.5	0.7
	2050	0.5	0.9	1.4
	2100	0.9	2.2	4.6

Table F-2. LSL relative to year 2000, in feet, based on Kopp et al. (2014) projections.

Appendix G. Quality Assurance Procedures

G.1 Project Quality Assurance Plan

The project team assures quality by these methods:

1. Clearly document all procedures in the Interim Study, consistent with a standard of reproducibility common in scholarly journals, especially those of the relevant fields of earth science, engineering, economics, and social science. To the extent practical, the project team offers underlying data, but does not hold itself to a higher standard of providing data than those of journals in their fields. For the sake of brevity and efficiency, the project team does not commit to reproducing or explaining as in a textbook any prior art that is well documented elsewhere. The project team cites those works for the reader's benefit and provides complete bibliographic references.

2. This is an applied research project, not basic research. The project team does not commit to search for data that *may* exist, *ought* to exist, or *ought* to be available to the public. It does not commit to improve on the state of the practice or state of the art, although as scholars the project team does take advantage of convenient opportunities to advance the state of the art in a few useful and important ways. (See Appendix E for details.)

3. All data and procedures are based to the maximum extent practical on published, peer-reviewed, highly cited works. For the sake of scientific rigor, the project team uses no proprietary data or procedures. When confronted with a choice among competing procedures or data sources, the project team selects the ones that are both practical and most well accepted. The project team does not demand absolute consensus among relevant experts, but does aim for the best available choice.

4. The baseline for all procedures and data is the 2005 *Mitigation Saves* study. The project team does not take the trouble to repeat any defense of the 2005 *Mitigation Saves* study procedures or choices that are already documented in that earlier report. That work has been highly cited and has stood the test of time over the decade since its publication.

5. Where there is significant uncertainty or no census, the project team leans toward a conservative procedure, e.g., one that estimates lower benefits or higher costs.

6. The goal of the Interim Study is to provide best estimates of the BCR of natural hazard mitigation. Still, the project team tries to acknowledge significant uncertainty where it exists and test the sensitivity of BCR to major uncertain variables using a deterministic procedure call tornado-diagram analysis, as in the 2005 *Mitigation Saves* study.

7. Perform internal checks of all results. Project team members choose internal QA procedures that best suit their organization, as long as those procedures satisfy that project team's oversight committee members. (Regarding the oversight committee, see item 8.)

8. NIBS has engaged a large oversight committee of highly qualified experts. At least two experts consider each topic: flood, wind, earthquake, fire, economics, social sciences, and building codes. Oversight committee members generally include one scholar and one practitioner for each topic, to better ensure that both theory and practice are properly considered. The oversight committee formally met three times: a kickoff web meeting in December 2016, at the time of delivering the 33% draft to FEMA (February 2017), and email to review the near-final draft report (September 2017). At these meetings, the project team presented the in-progress or near-final draft report to the oversight committee, who had two opportunities to provide feedback: during the presentation meeting and online during the week after the presentation meeting. The project team committed to addressing the oversight committee members' comments, although, to retain independence, the project team did not commit to completely satisfying the oversight committee on every point. Committee members (listed in Table G-1) were selected and appointed by the Institute in consultation with the project team and the FEMA contract officers. They work as subcontractors of the Institute, and are therefore independent of the project team.

9. The Institute, project team, and oversight committee formally met with a stakeholder group in February 2017 to optimize the project's objectives and the form of its deliverables. The main goal of these deliverables is to inform common natural hazard mitigation decisions. They should be readily usable by people who make natural hazard risk-mitigation decisions, people who offer or formulate incentives to others to engage in natural hazard risk mitigation, or people who further develop risk-mitigation techniques and analysis procedures. NIBS and the project team also meet informally with other stakeholders such as economists and engineers from FEMA, DHS, and OMB, as well as other potential users of the Interim Study.

Topic	Person	Affiliation
Flood	Neil Blais[(a)]	Blais & Associates
	Gavin Smith	Coastal Resilience Center of Excellence, University of North Carolina
Wind	Tim Reinhold[(b)]	Insurance Institute for Business & Home Safety
	Peter Vickery	Applied Research Associates
Earthquake	Brent Woodworth[(b)]	Los Angeles Emergency Preparedness Foundation
	Lucy Jones	Dr. Lucy Jones Center for Science and Society
Wildfire	Mark Finney	U.S. Forest Service
	Kim Zagaris	California Office of Emergency Services
Economics	Phil Ganderton[(b)]	University of New Mexico
	Adam Rose[(b)]	University of Southern California
Social science	Lori Peek	Natural Hazards Center, University of Colorado
	Stan Drake	City of Moore, Oklahoma
	Jennifer Helgeson	National Institute of Standards and Technology
Codes	Steve Winkel	The Preview Group
	Terry McAllister	National Institute of Standards and Technology
	Tim Ryan	City of Overland Park, Kansas

(a) Committee chair
(b) Involved in the 2005 *Mitigation Saves* study.

Table G-1. 2017 Mitigation Saves study oversight committee.

G.2 QA Procedures for Seismic Hazard and Seismic Vulnerability

Approach 1: Investigator A documents the procedures in terms of what is given, what is required, and then presents the solution, carrying out the calculations specified in the solution and documenting one or two samples of the calculations from end to end. The documentation and all relevant data are then provided to investigator B, who answers the following questions:

1. Is the documentation clear? If not, investigator B requests that investigator A revises the calculations to make all the steps clear and easy to follow.
2. Do the calculations agree with standard practice? If you are not sure, ask investigator A to revise the calculations so that all equations are cited back to a source that you can easily find.
3. Are the sample calculations correct, and do they agree with the results shown in the spreadsheet? If not, flag errors and ask investigator A to correct them.
4. Check the first and last output records.
5. Check the output records that are somehow highest and somehow lowest.
6. Spot-check 2 records at random from the middle.

Approach 2*:* Investigator A documents the procedures. Investigators A and B (or investigators B and C) carry out the calculations independently. If their results agree, it suggests that the documentation is clear and the calculations are correct.

Appendix H. Discount Rate

H.1 Options for Selecting the Discount Rate

The project team considered four options for selecting a discount rate for use in the study, and discussed them with economists at FEMA and OMB and with the economists on the oversight committee. See the options recapped below, with their advantages and disadvantages. With the approval of the oversight committee, the project team selected Option 3 as the best compromise.

1. Use the real interest rate (after-inflation cost of capital, as currently utilized in the Interim Study) as the discount rate.

   Advantages: Consistent with the 2005 *Mitigation Saves* study. Consistent with principles of engineering economics.

   Disadvantages: not useful to OMB.

2. Use OMB Circular A-4 as the discount rate (2003).

   Advantages: useful to OMB.

   Disadvantages: inconsistent with the 2005 *Mitigation Saves* study. Inconsistent with principles of engineering economics. Seems to conflate IRR analysis with BCA.

3. Use Option 1 as baseline and publish Option 2 in a parallel section.

   Advantages: consistent with the 2005 *Mitigation Saves* study. Consistent with principles of engineering economics. Provides OMB with the data they need.

   Disadvantages: none apparent. Possibly confusing to some readers, but doubtful, since the 2005 *Mitigation Saves* study project team heard no objections to the 2005 *Mitigation Saves* study tornado diagram analysis used to test sensitivity of BCR to discount rate.

4. Reverse of 3: Circular A-4 for baseline, real cost of borrowing in sensitivity study in a parallel section, appendix, or other separate section (OMB 2003).

   Advantages: provides OMB the data they need, and presents in an appendix or elsewhere results that are consistent with the 2005 *Mitigation Saves* study.

   Disadvantages: baseline is inconsistent with the 2005 *Mitigation Saves* study and principles of engineering economics.

After discussion among project team, FEMA, and oversight committee economists (Ganderton and Rose), option 3 appears best.

H.2 Selected Discount Rate Values

H.2.1 Real Cost of Borrowing

r = real cost of borrowing = long-term cost of borrowing, less inflation.

Residential real cost of borrowing. For residential 15-year and 30-year fixed-rate loans and jumbo loan, Wells Fargo is currently charging 0.0401 to 0.0442 (https://www.wellsfargo.com/mortgage/rates/). This uses a conservative (higher) figure: that of 30-year fixed jumbo as of December 2016, 0.0431. The Trading Economics website reports that the December 2016 U.S. inflation rate was 0.021 (https://tradingeconomics.com/). Thus,

$$r_{RES} = 0.0431 - 0.0210 = 0.0221.$$

Commercial real cost of borrowing. For a commercial mortgage, the interest rate is usually 0.5% to 1.0% higher than residential mortgage rates (AdvisoryHQ 2017), but as of this writing the two are approximately equal. Commercial Loan Direct is charging 3.7% to 4.335% (https://www.commercialloandirect.com/commercial-rates.php. A December 2016 U.S. Securities and Exchange Commission (SEC) filing reported that JP Morgan Chase is currently charging 2.86% to 5.35%, with a weighted average mortgage rate of 4.23% (http://www.secinfo.com/d1evd6.w48g.htm, page 132), so take

$$r_{NRES} = 0.0423 - 0.021 = 0.0213.$$

Government real cost of borrowing. Government borrowing is discounted using the composite rate for I bonds issued by the U.S. Department of the Treasury, which from November 1, 2016, through April 30, 2017, is 0.0276 (https://www.treasurydirect.gov/indiv/research/indepth/ibonds/res_ibonds_iratesandterms.htm). Also note that the current return on Treasury inflation-protected securities (TIPS) real yield, as of November 1, 2016, was 0.0069 for a 30-year term, which agrees well with the value of r_{GOV} used here:

$$r_{GOV} = 0.0276 - 0.0210 = 0.0066$$

H.2.2 Discount Rates According to OMB Circular A-4

For purposes of calculating BCR for the benefit of OMB, use the values directed by OMB Circular A-4 (2003):

$$r_{A4\text{-}1} = 0.07$$
$$r_{A4\text{-}2} = 0.03$$

Appendix I. Actual Economic Life of North American Buildings

BCA requires a duration over which to recognize the benefit of the investment. BCRs for exceeding code require an estimate of the actual service life of new buildings—the number of years between when they are built and when they are demolished. BCRs for federal mitigation grants require an estimate of the remaining life of an existing building or of the part of a building that is being remediated. The 2005 *Mitigation Saves* study assumed a useful life of 50 years for retrofits to ordinary buildings and 100 years for lifeline facilities.

ASCE 7 encodes a 50-year design life of new buildings in the wind and earthquake design maps of ASCE 7-10, but design life is not the same thing as actual service life. Emporis offers a database of high-rise buildings (generally 8 or more stories) worldwide. In the United States, the average existing high-rise building is already 50 years old, and 25% are already almost 70 years old. While the database obviously contains no data on buildings that have been demolished, it suggests that the true service life of any particular new U.S. building may be far longer than the design life assumed in ASCE 7.

Several sources offer guidance without underlying evidence. One highly cited work (Börjesson and Gustavsson 2000) suggest a building life cycle of 50 to 100 years, but not for U.S. construction. The U.S. Department of Defense assumes a 40-year useful life in life-cycle cost analyses (http://wbdg.org/FFC/DOD/UFC/ufc_1_200_02_2016.pdf). DOE suggests that commercial buildings have median lifetimes of 50 to 65 years, (http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=3.2.7).

O'Connor (2004) presents a rare work that offers observations of actual life of particular buildings: a demolition survey in Minneapolis/St Paul that captured building age, building type, structural material, and reason for demolition for 227 buildings that were demolished between 2000 and 2003. These included 122 residential and 105 nonresidential buildings, including 148 wood, 57 concrete, 10 steel, and the remaining 12 various combinations. She does not present an average age of demolished buildings, but rather the number of buildings by range of age at demolition, in 25-year increments (0-25, 26-50, 51-75, 76-100, and 101+). Using the midpoint of each age group one can estimate that the average building demolished between 2000 and 2003 in Minneapolis/St Paul was 73 years old. One can also estimate the figures for residential (89 years) and nonresidential (55 years). Maintenance costs and redevelopment dominate the reasons for demolition. O'Connor does not speculate on how life expectancy might differ in other locations or over time, e.g., during other points in the business cycle.

The limited available data support an actual service life of a building between 50 and 75 years, with the value depending largely on maintenance costs and redevelopment. It seems reasonable to take the service life of buildings in harsher environments, especially in coastal areas where maintenance costs tend to be higher, as 50 years, and that of buildings farther from the shoreline as 75 years.

Appendix J. Cost of Greater Elevation

The study of above-code measures examines, among other things, increasing the elevation of houses for greater flood resistance. A common approach to adding elevation is to raise the first floor on wooden piles, for which the construction cost appears in RSMeans 2017 Assemblies Cost Data, section A1020 160 2220. One can estimate the cost to raise a single-family dwelling as $33 per foot of elevation per pile, and assume 25 piles required (spacing at 12-foot centers, average plan area of 2400 sf, 9 additional piles at the perimeter; USCB 2010b), or $825 per foot of elevation. Wooden stairs add $325 per foot of elevation (RSMeans C2010 110 1150), for a total of approximately $1150 per foot of elevation.

Some houses have wheelchair ramps. How many, and at what cost? Examination of 682 sample houses in 5 coastal cities listed in vrbo.com suggests that approximately 5% are wheelchair accessible. (Miami, FL: 6 of 101 are wheelchair accessible = 6%; Biloxi, MS: 6 of 26 = 23%; Galveston, TX: 18 of 459: 4%; Charleston, SC: 1 of 54 = 2%; Tampa, FL 5 of 42: 12%; total 36 of 682 = 5%). These data imply that on the order of 5% of new homes with greater elevation would also have wheelchair ramps. The 5% figure coincidentally agrees with HUD requirements that 5% of federally funded new homes in developments must comply with ADA requirements, and must therefore have wheelchair ramps. Realistically, the figure could rise in coming decades as the American population ages, but one can neglect this (possibly second-order) consideration. An informal survey of online estimates of the cost of permanent wheelchair ramps suggests costs range widely, from $1,000 to $3,000 per foot of elevation. (Sources: NCSU 2004, Networx 2011, ProMatcher 2017, Angies List 2013. Add 0.05 × $2000 = $100 per foot of elevation for wheelchair ramps, accounting for the fact that only some new houses will be built with wheelchair ramps.

With nominal additional costs for utility risers and additional exterior closure material for ground-level storage space, the total cost is therefore approximately $1,300 per foot of elevation.

Appendix K. Details of Seismic Vulnerability

K.1 Calculating the Capacity Curve

Start by calculating the parameters of the capacity curve. It is defined by four parameters: D_y, A_y, D_u, and A_u. It is linear from (0,0) to (D_y, A_y), describes a portion of an ellipse between (D_y, A_y) and (D_u, A_u), and is flat to the right of D_u. For derivation of the following equations, see Porter (2009a and b), which draw on earlier editions of FEMA (2012e). One calculates these four parameter values from design parameters C_s, T_e, and I_e, as follows:

Let,

C_s = seismic response coefficient in the language of ASCE 7-10 Chapter 11. Hazus developers refer to C_s as design strength.

T_e = approximate (elastic) fundamental period of the as-is (I_e = 1.0) building. This is the mean estimate of elastic period, not the conservative (low) value from ASCE 7-10. For code-level design, one could use best-estimate values derived from regression analysis of actual building response by Chopra and Goel (2000). Alternatively, one could use the values tabulated by FEMA (2012e) in Table 5.5. The latter seems simpler and offers more assurance of consistency with Hazus. T_e is a function solely of model building type. See Table K-1.

I_e = (earthquake) importance factor from ASCE 7-10 Chapter 11.

Then using the equations in Figure 5.4 of FEMA (2012e):

$$A_y = \frac{C_s \gamma}{\alpha_1} \cdot I_e$$

(Equation K-1)

$$D_y = \frac{9.8 A_y T_e^2}{I_e}$$

(Equation K-2)

$$A_u = \lambda A_y$$

(Equation K-3)

$$D_u = \lambda \mu D_y$$

(Equation K-4)

The parameters γ, α_1, α_2, and λ vary by model building type and are tabulated in FEMA (2012e) Chapter 5. Table K-1 repeats them for convenient reference. The reader who is familiar with the Hazus methodology may notice the slight difference between Equations K-1 and K-2 and their counterparts in FEMA (2012e): I_e appears here but not there. It appears in the numerator of Equation K-1 because strength increases in proportion to I_e. It appears in the denominator of Equation K-2 to keep D_y constant regardless of A_y, that is, to increase stiffness in proportion to strength.

Building type	Roof height (ft)	Period T_e (sec)	Modal factor, weight, α_1	Modal factor, height, α_2	Overstrength ratio, yield γ	Overstrength ratio, ultimate, λ
W1	14	0.35	0.75	0.75	1.5	3
W2	24	0.4	0.75	0.75	1.5	2.5
S1L	24	0.5	0.8	0.75	1.5	3
S1M	60	1.08	0.8	0.75	1.25	3
S1H	156	2.21	0.75	0.6	1.1	3
S2L	24	0.4	0.75	0.75	1.5	2
S2M	60	0.86	0.75	0.75	1.25	2
S2H	156	1.77	0.65	0.6	1.1	2
S3	15	0.4	0.75	0.75	1.5	2
S4L	24	0.35	0.75	0.75	1.5	2.25
S4M	60	0.65	0.75	0.75	1.25	2.25
S4H	156	1.32	0.65	0.6	1.1	2.25
S5L	24	0.35	0.75	0.75	1.5	2
S5M	60	0.65	0.75	0.75	1.25	2
S5H	156	1.32	0.65	0.6	1.1	2
C1L	20	0.4	0.8	0.75	1.5	3
C1M	50	0.75	0.8	0.75	1.25	3
C1H	120	1.45	0.75	0.6	1.1	3
C2L	20	0.35	0.75	0.75	1.5	2.5
C2M	50	0.56	0.75	0.75	1.25	2.5
C2H	120	1.09	0.65	0.6	1.1	2.5
C3L	20	0.35	0.75	0.75	1.5	2.25
C3M	50	0.56	0.75	0.75	1.25	2.25
C3H	120	1.09	0.65	0.6	1.1	2.25
PC1	15	0.35	0.5	0.75	1.5	2
PC2L	20	0.35	0.75	0.75	1.5	2
PC2M	50	0.56	0.75	0.75	1.25	2
PC2H	120	1.09	0.65	0.6	1.1	2
RM1L	20	0.35	0.75	0.75	1.5	2
RM1M	50	0.56	0.75	0.75	1.25	2
RM2L	20	0.35	0.75	0.75	1.5	2
RM2M	50	0.56	0.75	0.75	1.25	2
RM2H	120	1.09	0.65	0.6	1.1	2
URML	15	0.35	0.5	0.75	1.5	2
URMM	35	0.5	0.75	0.75	1.25	2
MH	10	0.35	1	1	1.5	2

Table K-1. Capacity curve parameters.

Values of C_s. Values of S_S range from 0.037g (North Dakota) to 3.06g (northwest Tennessee). S_1 ranges from 0.026g (central Texas) to 1.26g (northwest Tennessee), using maps of MCE_R in ASCE 7-10. Depending on site conditions, S_{MS} could range from 0.033g to 3.67g; SM1 from 0.021g to 2.5g, considering F_a and F_v values from the 2015 NEHRP Provisions Tables 11.4-1 and 11.4-2. R-values range from 1 to 8 (ASCE 7-10 Table 12.2-1). All this implies that C_s values can range from less than 0.01g to greater than 3g, more than two orders of magnitude. The project team therefore constructed seismic vulnerability functions for buildings with C_s values (in terms of 5% damped elastic spectral acceleration response at 0.2-sec period and in at 1-sec period) in 31 logarithmic increments of 10^{-2}, $10^{-1.9}$, … 10^{1} g.

Building type	High code μ
W1	8
W2	8
S1L	8
S1M	5.3
S1H	4
S2L	8
S2M	5.3
S2H	4
S3	8
S4L	8
S4M	5.3
S4H	4
S5L	Obsolete
S5M	Obsolete
S5H	Obsolete
C1L	8
C1M	5.3
C1H	4
C2L	8
C2M	5.3
C2H	4
C3L	Obsolete
C3M	Obsolete
C3H	Obsolete
PC1	8
PC2L	8
PC2M	5.3
PC2H	4
RM1L	8
RM1M	5.3
RM2L	8
RM2M	5.3
RM2H	4
URML	Obsolete
URMM	Obsolete
MH	6

Table K-2. Values of ductility capacity μ.

Values of I_e. This examines values of I_e equal to 1.0, 1.25, 1.5, 2.0, 3.0, … 8.0. (The last of which would be like designing the most ductile system to be elastic.)

MBTID	Building type	κ (5.5≤M<7.5)
1	W1	0.8
2	W2	0.6
3	S1L	0.6
4	S1M	0.6
5	S1H	0.6
6	S2L	0.5
7	S2M	0.5
8	S2H	0.5
9	S3	0.5
10	S4L	0.5
11	S4M	0.5
12	S4H	0.5
13	S5L	0.3
14	S5M	0.3
15	S5H	0.3
16	C1L	0.6
17	C1M	0.6
18	C1H	0.6
19	C2L	0.6
20	C2M	0.6
21	C2H	0.6
22	C3L	0.3
23	C3M	0.3
24	C3H	0.3
25	PC1	0.5
26	PC2L	0.5
27	PC2M	0.5
28	PC2H	0.5
29	RM1L	0.6
30	RM1M	0.6
31	RM2L	0.6
32	RM2M	0.6
33	RM2H	0.6
34	URML	0.3
35	URMM	0.3
36	MH	0.4

Table K-3. Damping coefficients κ for medium-duration (5.5≤M<7.5) earthquakes and high-code buildings.

Select a set of S_d values at which to evaluate the capacity curve. This uses 51 logarithmic increments 10^{-3}, $10^{-2.9}$, … 10^2 inches. One calculates S_a for each value of S_d as follows:

$$\begin{aligned} S_a &= S_d A_y / D_y & S_d &< D_y \\ &= A_0 + b\sqrt{1 - \frac{(S_d - D_u)^2}{a^2}} & D_y \leqslant S_d &< D_u \\ &= A_u & D_u &\leqslant S_d \end{aligned}$$

(Equation K-5)

Where,

$$b = \frac{D_y(A_y - A_u)^2 - (D_y - D_u)A_y(A_y - A_u)}{(D_y - D_u)A_y - 2D_y(A_y - A_u)}$$

$$a = \sqrt{\frac{-D_y(D_y - D_u)b^2}{A_y(A_y - A_u + b)}}$$

$$A_0 = A_u - b$$

(Equation K-6)

At each value of S_d below D_y, effective damping equals elastic damping ratio B_E. For S_d above D_y, effective damping is calculated as:

$$B_{eff} = B_E + \kappa\left(\frac{2}{\pi}\left[1 - \frac{K_s}{K_E}\right]\right)$$

(Equation K-7)

Where,

$$K_s = \frac{S_a}{S_d}$$

(Equation K-8)

$$K_E = \frac{A_y}{D_y}$$

(Equation K-9)

This evaluates Equations K-1 through K-9 for each point on the capacity curve (that is, each S_d value) and for each combination of model building type, C_s level and I_e level. Note that one can exclude the obsolete model building types S5L, S5M, S5H (steel frame with unreinforced masonry (URM) infill, low- mid- and high-rise), C3L, C3M, C3H (low-, mid- and high-rise concrete frame with URM infill), and URML and URMM (low- and mid-rise unreinforced masonry buildings).

K.2 Calculate Input Motion for Each Point on the Capacity Curve

The index spectrum represents an idealized 5% damped response spectrum at various values of period T, in the space of spectral displacement response on the x axis and spectral acceleration response on the y axis. See Porter (2009a) for the derivation of the following relationships.

First determine whether the performance point lies on the constant-acceleration or constant velocity portion of the idealized response spectrum (ignoring the constant-displacement portion, which only the tallest buildings and rarest cases involve). The answer depends on whether the period at the performance point is less than or greater than the period corresponding to the intersection of the constant-acceleration and constant-velocity portions. Let T denote the period of the performance point, in seconds. As before, S_d is the *x*-coordinate of the performance point in inches and S_a is its *y*-coordinate in units of gravity. Then

$$T = 0.32\sqrt{S_d/S_a}$$

(Equation K-10)

Let T_{AVD} denote the period at which the constant-acceleration and constant-velocity portions of the response spectrum intersect. As shown in Porter (2009a), T_{AVD} varies by seismic domain (plate boundary, denoted by WUS (Western United States), or continental interior, denoted by CEUS (Central and Eastern United States)), magnitude M, distance from the fault rupture to the site R, NEHRP site class, and effective damping ratio B_{eff}. For probabilistic risk analysis, one uses M = 7, R = 20 km, and NEHRP site class = D. Under these constraints, one can find that T_{AVD} can be reasonably approximated as:

$$T_{AVD} = 2.67 \cdot B_{Eff}^3 - 1.73 \cdot B_{Eff}^2 + 1.09 \cdot B_{Eff} + 0.55$$

(Equation K-11)

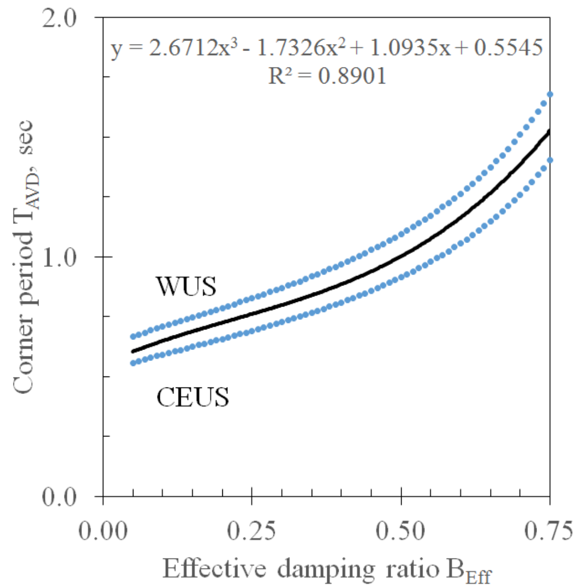


Figure K-1. Corner period T_{AVD} for M=7, R=20 km, soil=D, versus effective damping ratio.

Site class	SA02	F_a
D	≤0.40	1.60
D	0.50	1.54
D	0.60	1.47
D	0.70	1.40
D	0.80	1.31
D	0.90	1.20
D	1.00	1.15
D	1.10	1.10
D	1.20	1.04
D	≥1.30	1.00

Table K-4. F_a as a function of SA02.

Site class	$SA10_{BC}$	Fv
D	≤0.20	2.40
D	0.30	2.36
D	0.40	2.29
D	0.50	2.21
D	0.60	2.13
D	0.70	2.05
D	0.80	1.99
D	0.90	1.95
D	1.00	1.91
D	1.10	1.87
D	1.20	1.83
D	1.30	1.79
D	1.40	1.75
D	≥1.50	1.71

Table K-5. F_v as a function of SA10BC for site class D.

If $T \leq T_{AVD}$, one uses S_a, S_d, and B_{Eff} previously calculated for each point on the capacity curve, and calculates the site-amplified 5% damped short-period spectral acceleration response, denoted by SA02, using K-12.

$$SA02 = 2.12 S_a \Big/ \left(3.21 - 0.68 \ln\left[100 B_{eff}\right]\right)$$

(Equation K-12)

The site-amplified 5% damped 1-second spectral acceleration response, denoted by SA10, is given by,

$$SA10_{BC} = SA02 \cdot \frac{1}{(S_S/S_1)} \cdot \frac{1}{F_a(SA02)}$$

$$SA10 = SA10_{BC} \cdot F_v\left(SA10_{BC}\right)$$

(Equation K-13)

where (S_S/S_1) is the spectral acceleration response factor, taken here as 2.75 for simplicity (it takes on a value of 3.0 in CEUS and 2.5 in WUS). The term F_a(SA02) refers to the value of F_a given that the site-amplified 5%-damped short-period spectral acceleration response is SA02. Tables K-4 and K-5 give F_a(SA02) and $F_v(SA10_{BC})$ in 0.1-g increments for site class D.

If $T > T_{AVD}$, one uses S_a, S_d, and B_{Eff} previously calculated for each point on the capacity curve, calculates the site-amplified 5% damped 1-sec spectral acceleration response using

$$SA10 = 0.528 \cdot \sqrt{S_a S_d} \Big/ \left(2.31 - 0.41 \ln\left[100 B_{eff}\right]\right)$$

(Equation K-14)

and then the site-amplified 5% damped short-period spectral acceleration response is given by

$$SA02_{BC} = SA10 \cdot \left(S_S / S_1\right) \cdot \frac{1}{F_v\left(SA10\right)}$$
$$SA02 = SA02_{BC} \cdot F_a\left(SA02_{BC}\right)$$
(Equation K-15)

where (S_S/S_1) is taken as 2.75 as before, $F_v(SA10)$ refers to the value of F_v given that the site-amplified 5%-damped 1-second spectral acceleration response is SA10. Tables K-6 and K-7 give $F_a(SA02_{BC})$ and $F_v(SA10)$ in 0.1-g increments for site class D.

Repeat these calculations for each point on the capacity curve and for each combination of model building type, C_s level, and I_e level. As before, omit the obsolete model building types S5L, S5M, S5H, C3L, C3M, C3H, URML, and URMM.

Site class	$SA02_{BC}$	F_a
D	≤0.20	1.60
D	0.30	1.56
D	0.40	1.48
D	0.50	1.40
D	0.60	1.32
D	0.70	1.24
D	0.80	1.18
D	0.90	1.14
D	1.00	1.10
D	1.10	1.06
D	1.20	1.02
D	≥1.30	1.00

Table K-6. F_a as a function of $SA02_{BC}$ for site class D.

Site class	SA10	F_v
D	≤0.60	2.40
D	0.70	2.37
D	0.80	2.33
D	0.90	2.29
D	1.00	2.25
D	1.10	2.21
D	1.20	2.17
D	1.30	2.12
D	1.40	2.07
D	1.50	2.01
D	1.60	1.99
D	1.70	1.96
D	1.80	1.94
D	1.90	1.91
D	2.00	1.89
D	2.10	1.86
D	2.20	1.83
D	2.30	1.80
D	2.40	1.77
D	2.50	1.73
D	≥2.60	1.71

Table K-7. F_v as a function of SA10 for site class D.

K.3 Calculate Damage for Each Point on the Capacity Curve

The damageable building components are idealized as comprising three parts: displacement-sensitive structural elements, displacement-sensitive nonstructural elements, and acceleration-sensitive nonstructural elements, each with five possible damage states in the following order: none (damage state is shown by d = 0), slight (d = 1), moderate (d = 2), extensive (d = 3), and complete (d = 4). Part of the structure can also collapse; therefore, the damage state is represented by d = 5. The probabilistic damage state of each of these three elements is evaluated using fragility functions that are idealized as lognormal cumulative distribution functions. The probability that an element is in one of these damage states is taken as the difference in probability between it and that of the next higher damage state.

Equation K-16 represents the probabilistic damage state to the structural elements. Equation K-17 does the same for the nonstructural drift-sensitive element (note no damage state 5, which refers to collapse). Equation K-18 does the same for the acceleration-sensitive element (note that the input parameter is S_a at the performance point, not S_d). In all three equations, $P[A|B]$ denotes the probability that statement A is true given that statement B is true, D_s denotes uncertain damage state of the structural element (the meaning of the subscript s), D_{nd} that of the nonstructural drift-sensitive element (note subscript nd), and D_{na} that of the nonstructural acceleration-sensitive element (na). Parameter d denotes a particular value of D_s, D_{nd}, or D_{na} (0 = undamaged, 1 = slight damage, 2 = moderate damage, 3 = extensive damage, 4 = complete, and 5 = collapse). S_d denotes spectral displacement response at the performance point, () denotes the standard normal cumulative distribution function evaluated at the expression in parentheses, ln() denotes the natural logarithm of the expression inside the parentheses. The parameters θ and β are the median capacity and standard deviation of the natural logarithm of capacity. They vary by element, building type, and damage state. Their damage states are denoted by their first subscript, and the element to which they refer is denoted by the second subscript: For example, $\theta_{1,s}$ denotes the median capacity of damage state 1 for the structural element (s). The parameter P_c denotes the fraction of all building occupiable floor area that is already in the complete damage state that is also collapsed. One repeats these calculations for each point on the capacity curve and for each combination of model building type, C_s level and I_e level.

$$
\begin{aligned}
P\left[D_s = d \middle| S_d = x\right] &= 1 - \Phi\left(\frac{\ln\left(x/\theta_{1,s}\right)}{\beta_{1,s}}\right) && d = 0 \\
&= \Phi\left(\frac{\ln\left(x/\theta_{d,s}\right)}{\beta_{d,s}}\right) - \Phi\left(\frac{\ln\left(x/\theta_{d+1,s}\right)}{\beta_{d+1,s}}\right) && 1 \le d \le 3 \\
&= \left(1 - P_c\right)\Phi\left(\frac{\ln\left(x/\theta_{4,s}\right)}{\beta_{4,s}}\right) && d = 4 \\
&= P_c\Phi\left(\frac{\ln\left(x/\theta_{4,s}\right)}{\beta_{4,s}}\right) && d = 5
\end{aligned}
$$

(Equation K-16)

$$
\begin{aligned}
P\left[D_{nd} = d \middle| S_d = x\right] &= 1 - \Phi\left(\frac{\ln\left(x/\theta_{1,nd}\right)}{\beta_{1,nd}}\right) && d = 0 \\
&= \Phi\left(\frac{\ln\left(x/\theta_{d,nd}\right)}{\beta_{d,nd}}\right) - \Phi\left(\frac{\ln\left(x/\theta_{d+1,nd}\right)}{\beta_{d+1,nd}}\right) && 1 \le d \le 3 \\
&= \Phi\left(\frac{\ln\left(x/\theta_{4,nd}\right)}{\beta_{4,nd}}\right) && d = 4
\end{aligned}
$$

(Equation K-17)

$$
\begin{aligned}
P\left[D_{na} = d \middle| S_a = y\right] &= 1 - \Phi\left(\frac{\ln\left(y/\theta_{1,na}\right)}{\beta_{1,na}}\right) && d = 0 \\
&= \Phi\left(\frac{\ln\left(y/\theta_{d,na}\right)}{\beta_{d,na}}\right) - \Phi\left(\frac{\ln\left(y/\theta_{d+1,na}\right)}{\beta_{d+1,na}}\right) && 1 \le d \le 3 \\
&= \Phi\left(\frac{\ln\left(y/\theta_{4,na}\right)}{\beta_{4,na}}\right) && d = 4
\end{aligned}
$$

(Equation K-18)

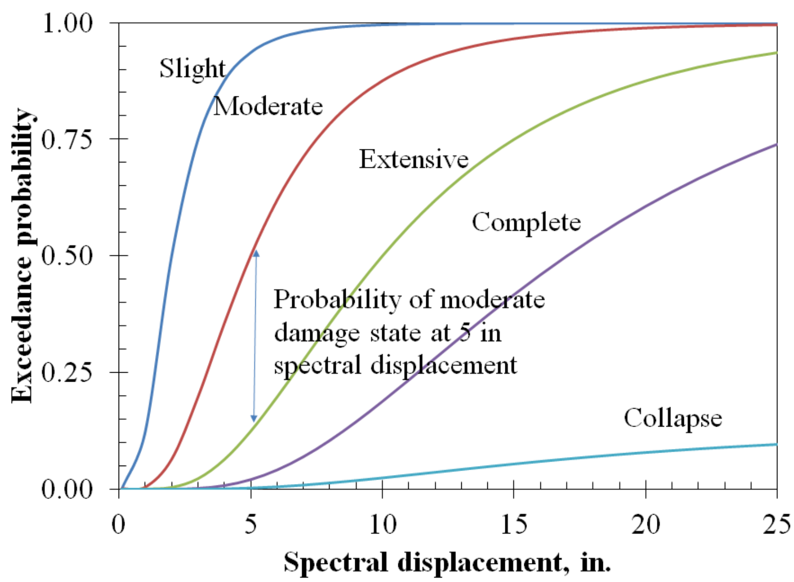


Figure K-2. Illustration of probabilistic damage state for structural components.

For any building type and performance point (S_d, S_a), calculate the 13 probabilities: the probability that the structural component is in each of 5 damage states; the probability that the nonstructural drift sensitive component is in each of 4 damage states, and the probability that the nonstructural acceleration-sensitive component is in each of 4 damage states. The calculation requires (S_d, S_a), 12 values of θ (one for each of 3 components and each of 4 damage states), 12 β values (one for each of 3 components and each of 4 damage states), and 1 value for P_c.

Repeat for each combination of model building type, C_s level and I_e level, omitting the obsolete model building types S5L, S5M, S5H, C3L, C3M, C3H, URML, and URMM.

K.4 Calculate Building Repair Cost as a Fraction of Building Replacement Cost

One assigns an expected value of loss to each element and damage state, and applies the theorem of total probability to estimate the expected value of loss for the building as a whole (denoted by L_b), as shown in Equation K-19. In the equation, L_b denotes the expected value of loss as a fraction of value exposed given excitation x and $L_{d,s}$ denotes the expected value of loss given the structural element in a particular damage state d. In the case of repair costs, losses accumulate from all three elements. The first summand in Equation K-19 refers to repair costs to the structural element (note the subscript *s*). The second summand adds up repair costs for the nonstructural drift-sensitive element (note subscript *nd*). The third adds repair costs for the nonstructural acceleration-sensitive element (note subscript *na*). See Table K-8 for parameter values of repair cost $L_{d,s}$, Table K-9 for $L_{d,ns}$, and Table K-10 for $L_{d,na}$, all adapted from FEMA (2012e). These parameter values vary by occupancy class, so one repeats for each combination of model building type, occupancy class, C_s level and I_e level.

$$L_b = \sum_{d=1}^{4} P\left[D_s = d \mid S_d = x\right] \cdot L_{d,s} + \sum_{d=1}^{4} P\left[D_{nd} = d \mid S_d = x\right] \cdot L_{d,nd} + \sum_{d=1}^{4} P\left[D_{na} = d \mid S_a = y\right] \cdot L_{d,na}$$

(Equation K-19)

No.	Label	Occupancy Class	1. Slight	2. Mod	3. Ext	4. Com
1	RES1	Single-Family Dwelling	0.005	0.023	0.117	0.234
2	RES2	Mobile Home	0.004	0.024	0.073	0.244
3-8	RES3a-f	Multi-Family Dwelling	0.003	0.014	0.069	0.138
9	RES4	Temporary Lodging	0.002	0.014	0.068	0.136
10	RES5	Institutional Dormitory	0.004	0.019	0.094	0.188
11	RES6	Nursing Home	0.004	0.018	0.092	0.184
12	COM1	Retail Trade	0.006	0.029	0.147	0.294
13	COM2	Wholesale Trade	0.006	0.032	0.162	0.324
14	COM3	Personal and Repair Services	0.003	0.016	0.081	0.162
15	COM4	Professional/Technical/Business Services	0.004	0.019	0.096	0.192
16	COM5	Banks/Financial Institutions	0.003	0.014	0.069	0.138
17	COM6	Hospital	0.002	0.014	0.070	0.140
18	COM7	Medical Office/Clinic	0.003	0.014	0.072	0.144
19	COM8	Entertainment & Recreation	0.002	0.010	0.050	0.100
20	COM9	Theaters	0.003	0.012	0.061	0.122
21	COM10	Parking	0.013	0.061	0.304	0.609
22	IND1	Heavy	0.004	0.016	0.078	0.157
23	IND2	Light	0.004	0.016	0.078	0.157
24	IND3	Food/Drugs/Chemicals	0.004	0.016	0.078	0.157
25	IND4	Metals/Minerals Processing	0.004	0.016	0.078	0.157
26	IND5	High Technology	0.004	0.016	0.078	0.157
27	IND6	Construction	0.004	0.016	0.078	0.157
28	AGR1	Agriculture	0.008	0.046	0.231	0.462
29	REL1	Church/Membership Organization	0.003	0.020	0.099	0.198
30	GOV1	General Services	0.003	0.018	0.090	0.179
31	GOV2	Emergency Response	0.003	0.015	0.077	0.153
32	EDU1	Schools/Libraries	0.004	0.019	0.095	0.189
33	EDU2	Colleges/Universities	0.002	0.011	0.055	0.110

Table K-8. Structural repair costs as a fraction for building replacement cost new, $L_{d,s}$.

No.	Label	Occupancy Class	1. Slight	2. Mod	3. Ext	4. Com
1	RES1	Single-Family Dwelling	0.010	0.050	0.250	0.500
2	RES2	Mobile Home	0.008	0.038	0.189	0.378
3-8	RES3a-f	Multi-Family Dwelling	0.009	0.043	0.213	0.425
9	RES4	Temporary Lodging	0.009	0.043	0.216	0.432
10	RES5	Institutional Dormitory	0.008	0.040	0.200	0.400
11	RES6	Nursing Home	0.008	0.041	0.204	0.408
12	COM1	Retail Trade	0.006	0.027	0.138	0.275
13	COM2	Wholesale Trade	0.006	0.026	0.132	0.265
14	COM3	Personal and Repair Services	0.007	0.034	0.169	0.338
15	COM4	Professional/Technical/Business Services	0.007	0.033	0.164	0.329
16	COM5	Banks/Financial Institutions	0.007	0.034	0.172	0.345
17	COM6	Hospital	0.008	0.035	0.174	0.347
18	COM7	Medical Office/Clinic	0.007	0.034	0.172	0.344
19	COM8	Entertainment & Recreation	0.007	0.036	0.178	0.356
20	COM9	Theaters	0.007	0.035	0.176	0.351
21	COM10	Parking	0.004	0.017	0.087	0.174
22	IND1	Heavy	0.002	0.012	0.059	0.118
23	IND2	Light	0.002	0.012	0.059	0.118
24	IND3	Food/Drugs/Chemicals	0.002	0.012	0.059	0.118
25	IND4	Metals/Minerals Processing	0.002	0.012	0.059	0.118
26	IND5	High Technology	0.002	0.012	0.059	0.118
27	IND6	Construction	0.002	0.012	0.059	0.118
28	AGR1	Agriculture	0.000	0.008	0.038	0.077
29	REL1	Church/Membership Organization	0.008	0.033	0.163	0.326
30	GOV1	General Services	0.007	0.033	0.164	0.328
31	GOV2	Emergency Response	0.007	0.034	0.171	0.342
32	EDU1	Schools/Libraries	0.009	0.049	0.243	0.487
33	EDU2	Colleges/Universities	0.012	0.060	0.300	0.600

Table K-9. Nonstructural drift-sensitive repair costs as a fraction for building replacement cost new, $L_{d,nd}$.

No.	Label	Occupancy Class	1. Slight	2. Mod	3. Ext	4. Com
1	RES1	Single-Family Dwelling	0.005	0.027	0.080	0.266
2	RES2	Mobile Home	0.008	0.038	0.113	0.378
3-8	RES3a-f	Multi-Family Dwelling	0.008	0.043	0.131	0.437
9	RES4	Temporary Lodging	0.009	0.043	0.130	0.432
10	RES5	Institutional Dormitory	0.008	0.041	0.124	0.412
11	RES6	Nursing Home	0.008	0.041	0.122	0.408
12	COM1	Retail Trade	0.008	0.044	0.129	0.431
13	COM2	Wholesale Trade	0.008	0.042	0.124	0.411
14	COM3	Personal and Repair Services	0.010	0.050	0.150	0.500
15	COM4	Professional/Technical/Business Services	0.009	0.048	0.144	0.479
16	COM5	Banks/Financial Institutions	0.010	0.052	0.155	0.517
17	COM6	Hospital	0.010	0.051	0.154	0.513
18	COM7	Medical Office/Clinic	0.010	0.052	0.153	0.512
19	COM8	Entertainment & Recreation	0.011	0.054	0.163	0.544
20	COM9	Theaters	0.010	0.053	0.158	0.527
21	COM10	Parking	0.003	0.022	0.065	0.217
22	IND1	Heavy	0.014	0.072	0.218	0.725
23	IND2	Light	0.014	0.072	0.218	0.725
24	IND3	Food/Drugs/Chemicals	0.014	0.072	0.218	0.725
25	IND4	Metals/Minerals Processing	0.014	0.072	0.218	0.725
26	IND5	High Technology	0.014	0.072	0.218	0.725
27	IND6	Construction	0.014	0.072	0.218	0.725
28	AGR1	Agriculture	0.008	0.046	0.138	0.461
29	REL1	Church/Membership Organization	0.009	0.047	0.143	0.476
30	GOV1	General Services	0.010	0.049	0.148	0.493
31	GOV2	Emergency Response	0.010	0.051	0.151	0.505
32	EDU1	Schools/Libraries	0.007	0.032	0.097	0.324
33	EDU2	Colleges/Universities	0.006	0.029	0.087	0.290

Table K-10. Nonstructural acceleration-sensitive repair costs as a fraction for building replacement cost new, $L_{d,na}$.

K.5 Calculate Content Repair Cost as a Fraction of Content Replacement Cost

Content loss, L_c, is estimated solely as a function of nonstructural acceleration-sensitive damage, as in Equation K-20. See Table K-11 (adapted from FEMA 2012e) for values of the parameter $L_{d,c}$, which does not vary by occupancy class. The probability $P[D_{na} = d|S_a = y]$ is the same as in Equation K-19. Repeat for each combination of model building type (except the obsolete ones), C_s level and I_e level.

$$L_c = \sum_{d=1}^{4} P\left[D_{na} = d \middle| S_a = y\right] L_{d,c}$$

(Equation K-20)

	Acceleration sensitive nonstructural damage state			
	Slight	**Moderate**	**Extensive**	**Complete**
	$L_{1,c}$	**$L_{2,c}$**	**$L_{3,c}$**	**$L_{4,c}$**
All occupancies	0.01	0.05	0.25	0.50

Table K-11. Content damage factors conditioned on acceleration-sensitive damage states.

K.6 Calculate Injured Occupants as a Fraction of All Indoor Occupants

Injuries are estimated solely as a function of structural damage. Hazus recognizes four injury severity levels, from slight to fatal; see the definitions copied in Table K-12. Injured Occupants, L_i, are denoted by i1, i2, i3, and i4. Equation K-21 expresses the fraction of occupants in injury severity levels i1, i2, i3, and i4. The probabilities $P[D_s = d|S_d = x]$ are the same ones from Equation K-16. See FEMA (2012e) Tables 13.3 through 13.7 for values of $L_{d,i1}$ through $L_{d,i4}$; note that in these variables, d is a parameter that can take on the values 1, 2, 3, 4, and 5, so there are five values of $L_{d,i1}$, five of $L_{d,i2}$, etc., for a total of 20. One calculates L_{i1}, L_{i2}, L_{i3}, and L_{i4} for each point on the capacity curve. Repeat for each combination of model building type (except the obsolete ones), C_s level and I_e level.

$$L_{i1} = \sum_{d=1}^{5} P\left[D_s = d \left| S_d = x\right.\right] L_{d,i1}$$

$$L_{i2} = \sum_{d=1}^{5} P\left[D_s = d \left| S_d = x\right.\right] L_{d,i2}$$

$$L_{i3} = \sum_{d=1}^{5} P\left[D_s = d \left| S_d = x\right.\right] L_{d,i3}$$

$$L_{i4} = \sum_{d=1}^{5} P\left[D_s = d \left| S_d = x\right.\right] L_{d,i4}$$

(Equation K-21)

Injury Severity Level	Injury Description
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of lesser severity that could be self treated are not estimated by Hazus.
Severity 2	Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status. Some examples are third degree burns or second degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration or exposure.
Severity 3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. Some examples are: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.
Severity 4	Instantaneously killed or mortally injured

Table K-12. The injury severity levels in Hazus.

K.7 Calculate Loss of Function Duration

Duration of loss of function (recovery time in Hazus terminology) is also estimated solely as a function of structural damage and occupancy class. The expected value of building recovery time L_t, in days is given by Equation K-22. In this equation, the probabilities $P[D_s = d|S_d = x]$ are the same as in Equation K-16. In the equation, $L_{d,t}$ denotes the duration of loss of function for structural damage state d. It varies by occupancy class. See FEMA (2012e) Table 15.10 for building recovery time by damage state and occupancy class. Note that the loss of function duration for collapse ($D_s = 5$) is the same as for complete structural damage, so L_{5t} is taken as the value of L_{4t}, hence the second summand postmultiplies the collapse probability by L_{4t}.

$$L_t = \sum_{d=1}^{4} P\left[D_s = d \middle| S_d = x\right] L_{d,t} + P\left[D_s = 5 \middle| S_d = x\right] L_{4,t}$$

(Equation K-22)

Repeat the calculation of L_t for each point on the capacity curve and for each combination of model building type (except the obsolete ones), C_s value, I_e value, and occupancy class.

K.8 Calculate Direct, Indirect Time-Element Losses per Occupant

Rental and BI costs vary widely. Hazus offers some very old (1994) rental and disruption costs and warns that costs vary widely geographically. Therefore, it is important to revisit these amounts by calculating direct and indirect time-element losses L_{BI}, dollars per day per occupant. For residential occupancies RES1 through RES3 and RES5, assume monthly household furniture, higher commute costs, and miscellaneous other costs of $600/month/household, monthly house rental cost of $1500/month/household, and 2.5 people per household per OECD 2015, suggesting $28/person/day. For temporary lodging (RES4), assume lost revenue and wages equal to a typical average per-night hotel cost of $125 per day. For nursing homes (RES6), assume lost revenue and wages equal to the average daily cost of a private room in a nursing home, $248 per day (Mullin 2013). For nonresidential occupancies, estimate output loss (direct BI loss) per day of downtime as the ratio of industry wages and earnings to number of employees, converted to dollars per day. Results are shown in Table K-13.

For indirect BI, use IO analysis to estimate the per-dollar indirect BI loss *Q* resulting from $1.00 of direct BI in a given occupancy class. Calculate *Q* for each occupancy class by setting the output loss for that occupancy class to $1.00 and the output losses for all the other occupancy classes to 0. For example, to calculate *Q* for RES3 occupancy, set the output losses for RES1, RES2, RES4, …. EDU2 to 0, and the output loss for RES3 to 1.0. The resulting indirect BI to the entire economy can then be assigned to *Q* for RES3.

No.	Occupancy Class	Label	V_{BI}	Q
1	Single-Family Dwelling	RES1	$ 28.00	0.470
2	Mobile Home	RES2	$ 28.00	0.470
3	Multi-Family Dwelling	RES3a	$ 28.00	0.470
4	Multi-Family Dwelling	RES3b	$ 28.00	0.470
5	Multi-Family Dwelling	RES3c	$ 28.00	0.470
6	Multi-Family Dwelling	RES3d	$ 28.00	0.470
7	Multi-Family Dwelling	RES3e	$ 28.00	0.470
8	Multi-Family Dwelling	RES3f	$ 28.00	0.470
9	Temporary Lodging	RES4	$ 125.00	0.372
10	Institutional Dormitory	RES5	$ 28.00	0.470
11	Nursing Home	RES6	$ 248.00	0.500
12	Retail Trade	COM1	$ 132.28	0.037
13	Wholesale Trade	COM2	$ 295.21	0.033
14	Personal and Repair Services	COM3	$ 166.77	0.374
15	Professional/Technical Services	COM4	$ 414.93	0.016
16	Banks/Financial Institutions	COM5	$ 411.00	0.017
17	Hospital	COM6	$ 243.60	0.500
18	Medical Office/Clinic	COM7	$ 237.82	0.500
19	Entertainment & Recreation	COM8	$ 118.94	0.637
20	Theaters	COM9	$ 118.94	0.637
21	Parking	COM10	$ 118.94	0.374
22	Heavy	IND1	$ 312.49	0.260
23	Light	IND2	$ 242.04	0.438
24	Food/Drugs/Chemicals	IND3	$ 203.04	0.064
25	Metals/Minerals Processing	IND4	$ 233.26	0.009
26	High Technology	IND5	$ 465.98	0.041
27	Construction	IND6	$ 228.35	0.051
28	Agriculture	AGR1	$ 124.43	0.095
29	Church	REL1	$ 165.50	0.045
30	General Services	GOV1	$ 230.28	0.045
31	Emergency Response	GOV2	$ 230.28	0.045
32	Schools	EDU1	$ 162.11	0.035
33	Colleges/Universities	EDU2	$ 162.11	0.035

Table K-13. Output loss per day of downtime VBI and per-dollar indirect BI loss Q.

Thus, L_{BI}, the BI loss per occupant, can be estimated as a function of the number of days of loss of use L_t, as follows:

$$L_{BI} = V_{BI} \cdot (1+Q) \cdot L_t$$
(Equation K-23)

K.9 Calculate Fraction of Residents Displaced from their Homes

Following FEMA (2012e) Section 14.2, estimate displaced residents as the number of occupants of residences in the complete structural damage state, plus 90% of residents of multifamily dwellings in the extensive damage state. Equation K-24 expresses the L_{DR}, the fraction of residential occupants who will be displaced from their homes.

$$L_{dr} = P[D_s = 4|S_d = s] \text{ RES1 and RES2}$$
$$L_{dr} = 0.9 \cdot P[D_s = 3|S_d = s] + P[D_s = 4|S_d = s] \text{ RES3 through RES6}$$
(Equation K-24)

K.10 Calculate Collapse Probability Based on Number of Collapsed Buildings, Total Building Area

For building collapse, either use the Hazus methodology or a newer one suggested by Luco et al. (2007). The former would be more consistent with the foregoing analyses, but the latter is simple and has a much stronger analytical basis, e.g., Applied Technology Council (2009). Therefore, the latter is used to calculate collapse probability, $P_{col,}$ as a fraction of the number of buildings and the number of collapsed buildings, $N_{COL,}$ as a factor of total building area (sf).

Luco et al. (2007) and Applied Technology Council (2009) suggest that the capacity of a new building to resist collapse can be estimated as a lognormal cumulative distribution function. Porter (2015) showed that the data in Applied Technology Council (2009) imply that the median capacity θ can be estimated as 3.47 times MCE_R shaking (e.g., $3.47 \cdot C_S \cdot R \cdot 1.5$), where *R* denotes the ASCE 7-10 response modification coefficient from ASCE 7-10 Table 12.2-1. Table K-13 maps ASCE 7-10 building types to Hazus building types and shows the relevant *R* factors. The table shows three values for each model building type: one each for moderately high to very high, moderate, and low seismicity regions, based on judgment of the predominant ASCE 7-10 seismic force-resisting system (from Table 12.2-1) corresponding to each FEMA model building type in each region. "Seismicity region" refers here to the predominant seismicity region in the sense of FEMA P-154. Luco et al. (2007) use a value for the standard deviation of the natural logarithm of capacity equal to β = 0.8. Strength and collapse capacity increases with I_e.

For low-rise buildings (1-3 stories), calculate

$$\theta_{02} = 5.20 \cdot C_s \cdot R \cdot I_e$$
(Equation K-25)

For mid- and high-rise buildings (4+ stories)

$$\theta_{10} = 5.20 \cdot C_s \cdot R \cdot I_e$$
(Equation K-26)

And in both cases, use the same $\beta = 0.8$, so

$$P_{col} = \Phi\left(\frac{\ln\left(SA02/\theta_{02}\right)}{\beta}\right)$$

(Equation K-27)

$$P_{col} = \Phi\left(\frac{\ln\left(SA10/\theta_{10}\right)}{\beta}\right)$$

(Equation K-28)

MBTID	MBT	R, MH-VH seismicity	R, mod seismicity	R, low seismicity	ASCE 7-10 Table 12.2-1 seismic force-resisting system
1	W1	6.5	6.5	6.5	A15
2	W2	7	7	7	B22
3	S1L	8	4.5	3.5	C1, C3, C4
4	S1M	8	4.5	3.5	C1, C3, C4
5	S1H	8	4.5	3.5	C1, C3, C4
6	S2L	6	3.25	3.25	B2, B3, B3
7	S2M	6	3.25	3.25	B2, B3, B3
8	S2H	6	3.25	3.25	B2, B3, B3
9	S3	6	3.25	3.25	B2, B3, B3
10	S4L	7	6	6	D3, D4, D4
11	S4M	7	6	6	D3, D4, D4
12	S4H	7	6	6	D3, D4, D4
16	C1L	8	5	3	C5, C6, C7
17	C1M	8	5	3	C5, C6, C7
18	C1H	8	5	3	C5, C6, C7
19	C2L	6	5	5	B4, B5, B5
20	C2M	6	5	5	B4, B5, B5
21	C2H	6	5	5	B4, B5, B5
25	PC1	5	5	4	B8, B8, B9
26	PC2L	6	5	5	B4, B5, B5
27	PC2M	6	5	5	B4, B5, B5
28	PC2H	6	5	5	B4, B5, B5
29	RM1L	5	3.5	2	A7, A8, A9
30	RM1M	5	3.5	2	A7, A8, A9
31	RM2L	5	3.5	2	A7, A8, A9
32	RM2M	5	3.5	2	A7, A8, A9
33	RM2H	5	3.5	2	A7, A8, A9
36	MH	6.5	6.5	6.5	NIST 1995

Table K-14. Response modification coefficients R.

- States with predominantly moderately-high (MH) to very high (VH) seismicity: AK, CA, HI, MT, NV, OR, SC, TN, UT, WA
- States with predominantly moderate seismicity: AL, AR, AZ, CO, ID, KY, MA, ME, MO, NH, NJ, NM, NY, OK, VT, WY
- States with low seismicity: all others

P_{col} gives the fraction of buildings that collapse. The project team is also interested in the number of buildings that collapse. (Not the same as Hazus' estimated fraction of total square footage in the complete damage state that is assumed to be collapsed. The difference is that only a portion of the number of buildings in the complete damage state collapse, and only a portion of the area of those buildings actually collapse.) One can estimate number of collapsed buildings as a factor of total building area (sf) using:

$$N_{COL} = P_{col}/A_{avg}$$

(Equation K-29)

where A_{avg} denotes the average area of a single building and varies by occupancy class. One can calculate A_{avg} from Hazus' California inventory, dividing total building area by total building count (there does not appear to be a table in the documentation showing these values). See Table K-14.

OCCID	OccLabel	A_{avg}
1	RES1	1700
2	RES2	1100
3	RES3	6500
4	RES4	31100
5	RES5	22700
6	RES6	12100
7	COM1	71400
8	COM2	27400
9	COM3	9900
10	COM4	69100
11	COM5	3800
12	COM6	33100
13	COM7	6700
14	COM8	5000
15	COM9	4900
16	COM10	23800
17	IND1	23000
18	IND2	22700
19	IND3	25100
20	IND4	14800
21	IND5	25200
22	IND6	22300
23	AGR1	16300
24	REL1	15600
25	GOV1	9800
26	GOV2	8500
27	EDU1	25500
28	EDU2	33500

Table K-15. Average building area A_{avg} (square feet per building) inferred from Hazus.

K.11 Calculate Fraction of Buildings that are Red-Tagged, Number of Red-Tagged Buildings as a Factor of Total Building Area

Porter (2016a) shows that for every collapsed building, approximately 3.8 are red-tagged, N_R. Thus, the fraction of buildings that are red-tagged, P_R, can be estimated as:

$$P_r = 3.8 \cdot P_{col} \leq 1 - P_{col}$$

(Equation K-30)

The number of red-tagged buildings, as a factor of total building area in sf, can be estimated as:

$$N_R = P_r / A_{avg}$$

(Equation K-31)

K.12 Calculate Fraction of Buildings that are Yellow-Tagged, Number of Buildings that are Yellow-Tagged as a Factor of Total Building Area

Porter (2016a) shows that for every red-tagged building, approximately 13 are yellow-tagged, P_y.

$$P_y = 13 \cdot P_r \leq 1 - P_{col} - P_r$$

(Equation K-32)

And the number of yellow-tagged buildings, N_Y, as a factor of total building area in sf, can be estimated as:

$$N_Y = P_y / A_{avg}$$

(Equation K-33)

K.13 Calculate Persons Trapped in Collapsed Buildings as a Fraction of all Indoor Occupants

Porter (2016b) shows that on average, 25% of the area of buildings with at least some collapse actually experiences collapse, and estimates that 1 in 3 people occupying the collapsed area are trapped, not fatally injured, and need extrication. Thus, the number of trapped people in collapsed buildings, L_{tc}, requiring extrication, as a fraction of total indoor occupants, can be estimated by:

$$L_{tc} = 0.083 \cdot P_{col}$$

(Equation K-34)

K.14 Tabulating Vulnerability Functions

At this point, the analyst has calculated each of the following quantities for each combination of S_d, model building type (except obsolete ones), C_s, I_e, and occupancy class. (Others are calculated along the way, but these are the ones that matter for later).

Ground-motion-severity measures:

SA02: soil-amplified 5% damped spectral acceleration response at 0.2 sec period
SA10: soil-amplified 5% damped spectral acceleration response at 1.0 sec period

Loss measures:

L_b: mean building repair cost as a fraction of its replacement cost new
L_c: mean content repair cost as a fraction of its replacement cost new
L_{i1}: mean fraction of indoor occupants in injury severity level 1
L_{i2}: mean fraction of indoor occupants in injury severity level 2
L_{i3}: mean fraction of indoor occupants in injury severity level 3
L_{i4}: mean fraction of indoor occupants in injury severity level 4
L_t: mean duration of loss of function, in days
L_{BI}: mean business interruption loss per occupant per day, $
L_{dr}: mean fraction of residential occupants displaced from their homes

P_{col}: fraction of buildings that collapse
N_{COL}: number of collapsed buildings, as a factor of total building area (sf)
P_r: fraction of building that are red-tagged
N_R: number of red-tagged buildings, as a factor of total building area (sf)
P_y: fraction of building that are yellow-tagged
N_Y: number of yellow-tagged buildings, as a factor of total building area (sf)
N_{tc}: fraction of indoor occupants trapped in collapsed buildings

Recall that all of these quantities have been calculated for each of 51 points on the capacity curve, which were parameterized by pairs (S_d, S_a). One can then relate a value of SA02 to each loss measure, and construct a one-to-one pairing, creating a set of vulnerability and fragility functions that relate 5%-damped short-period spectral acceleration response SA02 to each measure. One can also create similar fragility and vulnerability functions in terms of 5%-damped 1.0-second spectral acceleration response, SA10.

Because of how one calculates the ground-motion-severity measures SA02 and SA10 from S_d, they are not the same 51 values for each combination of model building type, C_s, I_e, and occupancy class. It will be more convenient later to have losses tabulated at a consistent set of ground-motion-severity levels, so for each combination of 28 non-obsolete model building types, 28 occupancy classes, 31 C_s levels, and 10 I_e levels, one can linearly interpolate at 401 ground-motion input levels SA02 = {0.00g, 0.01g, 0.02g, … 4g} and again at 401 values of SA10 = {0.00g, 0.01g, 0.02g, … 4.00g}. Thus, at the end of this step, there are two very large tables ($28 \cdot 28 \cdot 31 \cdot 10 \cdot 401$ = 97.5 million records) containing the seismic vulnerability functions, with the fields listed in Box K-1 (functions in terms of 5%-damped short-period spectral acceleration response SA02) and Box K-2 (functions in terms of 5%-damped 1-second spectral acceleration response, SA10).

Box K-1. Vulnerability Functions in Terms of 5% Damped Short-Period Spectral Acceleration

MBTID: an integer index 1, 2, … 36 corresponding to model building types (only 28 used)
OCCID: an integer index 1, 2, … 28 corresponding to occupancy classes
CSID: an integer index 1, 2, … 31 corresponding to a C_s value
IEID: an integer index 1, 2, … 10 corresponding to an I_e value
SA02ID: an integer index 0, 1, 2, … 400 corresponding to a value of SA02
Model building type: one of {W1, W2, … MH}; omitting obsolete types, 28 types
Occupancy class: one of {RES1, RES2, RES3, … EDU2}, 28 classes
C_s: one of $\{10^{-2}, 10^{-1.9}, \ldots 10^{1}\}$, units of gravity, 31 values
I_e: one of {1, 1.25, 1.5, 2, 3, 4, 5, 6, 7, 8}, 10 values
SA02: one of x = {0.00, 0.01, 0.02, … 4.00}, units of gravity, 401 values
$y_b(x)$ = mean building repair cost as a fraction of its replacement cost new given SA02 = x
$y_c(x)$ = mean content repair cost as a fraction of its replacement cost new given SA02 = x
$y_{i1}(x)$ = mean fraction of indoor occupants in injury severity level 1 given SA02 = x
$y_{i2}(x)$ = mean fraction of indoor occupants in injury severity level 2 given SA02 = x
$y_{i3}(x)$ = mean fraction of indoor occupants in injury severity level 3 given SA02 = x
$y_{i4}(x)$ = mean fraction of indoor occupants in injury severity level 4 given SA02 = x
$y_T(x)$ = mean duration of loss of function, in days, given SA02 = x
$y_{BI}(x)$ = mean business interruption loss per occupant per day, $, given SA02 = x
$y_{dr}(x)$ = mean fraction of residential occupants displaced from their homes given SA02 = x
$y_{col}(x)$ = fraction of buildings that collapse, given SA02 = x
$y_{COL}(x)$ = number of collapsed buildings, as a factor of total building area (sf), given SA02 = x
$y_r(x)$ = fraction of buildings that are red-tagged, given SA02 = x
$y_R(x)$ = number of red-tagged buildings, as a factor of total building area (sf), given SA02 = x
$y_y(x)$ = fraction of building that are yellow-tagged, given SA02 = x
$y_Y(x)$ = number of yellow-tagged buildings, as factor of total building area (sf), given SA02 = x
$y_{tc}(x)$ = fraction of indoor occupants trapped in collapsed buildings, given SA02 = x

Box K-2. Vulnerability Functions in Terms of 5% Damped 1-Sec Spectral Acceleration SA10

MBTID: an integer index 1, 2, … 36 corresponding to model building types (only 28 used)
OCCID: an integer index 1, 2, … 28 corresponding to occupancy classes
CSID: an integer index 1, 2, … 31 corresponding to a C_s value
IEID: an integer index 1, 2, … 10 corresponding to an I_e value
SA10ID: an integer index 0, 1, 2, … 400 corresponding to a value of SA10
Model building type: one of {W1, W2, … MH}; omitting obsolete types, 28 types
Occupancy class: one of {RES1, RES2, RES3, … EDU2}, 28 classes
C_s: one of $\{10^{-2}, 10^{-1.9}, \ldots 10^{1}\}$, units of gravity, 31 values
I_e: one of {1, 1.25, 1.5, 2, 3, 4, 5, 6, 7, 8}, 10 values
SA10: one of {0.00, 0.01, 0.02, … 4.00}, units of gravity, 401 values
$y_b(x)$ = mean building repair cost as a fraction of its replacement cost new given SA10 = x
$y_c(x)$ = mean content repair cost as a fraction of its replacement cost new given SA10 = x
$y_{i1}(x)$ = mean fraction of indoor occupants in injury severity level 1 given SA10 = x
$y_{i2}(x)$ = mean fraction of indoor occupants in injury severity level 2 given SA10 = x
$y_{i3}(x)$ = mean fraction of indoor occupants in injury severity level 3 given SA10 = x
$y_{i4}(x)$ = mean fraction of indoor occupants in injury severity level 4 given SA10 = x
$y_T(x)$ = mean duration of loss of function, in days, given SA10 = x
$y_{BI}(x)$ = mean business interruption loss per occupant per day, $, given SA10 = x
$y_{dr}(x)$ = mean fraction of residential occupants displaced from their homes given SA10 = x
$y_{col}(x)$ = fraction of buildings that collapse, given SA10 = x
$y_{COL}(x)$ = number of collapsed buildings, as a factor of total building area (sf), given SA10 = x
$y_r(x)$ = fraction of buildings that are red-tagged, given SA10 = x
$y_R(x)$ = number of red-tagged buildings, as a factor of total building area (sf), given SA10 = x
$y_y(x)$ = fraction of building that are yellow-tagged, given SA10 = x
$y_Y(x)$ = number of yellow-tagged buildings as factor of total building area (sf), given SA10 = x
$y_{tc}(x)$ = fraction of indoor occupants trapped in collapsed buildings, given SA10 = x

K.15 Statewide Weighted-Average Vulnerability Functions

The project team desires wanted to express benefits and costs for design above code, without generating countless combinations of building type and occupancy class. Therefore, BCRs are estimated for a weighted average of the building types common in each state, with weights that reflect that state's recent construction practice.

Use the Hazus inventory of buildings with the highest design level as weights. That is, for states with high-code buildings, weight vulnerability functions by the total estimated statewide building area of high-code buildings for each model building type and occupancy class. For states with no high-code buildings, use the statewide total building area of moderate-code buildings as weights. In both cases, the weights are normalized so they add to 1.0.

Consider two averaging schemes: one that averages all types together, and one that distinguishes between residential and nonresidential construction. Thus, weights for the residential weighted average vulnerability functions use as weights the total square footage by model building type and occupancy class, but with zero weight for all nonresidential occupancy classes. Likewise, weights for the nonresidential weighted average vulnerability functions use as weights the total

Box K-3. Statewide Vulnerability Functions in Terms of 5% Damped Short-Period Spectral Acceleration SA02

MBTID: an integer 1xx, where xx denotes the state's U.S. Federal Information Processing Standard (FIPS) numeric code, as specified in FIPS Publication "FIPS PUB" 5-2 (https://catalog.data.gov/dataset/fips-state-codes)
OCCID: an integer index 100 to indicate all residential occupancies, 200 to indicate all nonresidential occupancies, or 0 to indicate all occupancy classes
CSID: an integer index 1, 2, … 31 corresponding to a C_s value
IEID: an integer index 1, 2, … 10 corresponding to an I_e value
SA02ID: an integer index 0, 1, 2, … 400 corresponding to a value of SA02
Model building type: XX, where XX is the FIPS state alpha (same as postal) code as specified in FIPS PUB 5-2
Occupancy class: one of {RES, NRES, AVG}, indicating average of all residential occupancies, nonresidential occupancies, or all occupancies, 3 classes
C_s: one of {10^{-2}, $10^{-1.9}$, … 10^{1}}, units of gravity, 31 values
I_e: one of {1, 1.25, 1.5, 2, 3, 4, 5, 6, 7, 8}, 10 values
SA02: one of {0.00, 0.01, 0.02, … 4.00}, units of gravity, 401 values
$y_b(x)$ = mean building repair cost as a fraction of its replacement cost new given SA02 = x

…

(same as Box K-1)

...

$y_{tc}(x)$ = fraction of indoor occupants trapped in collapsed buildings, given SA02 = x

square footage by model building type and occupancy class, but with zero weight for all residential occupancy classes.

Using the vulnerability functions listed in Appendix K.1.14, create a set of residential vulnerability functions, nonresidential vulnerability functions, and overall average vulnerability functions, one for each state. Thus, at the end of this step, there are two very large tables (50·3·31·10·401 = 18,646,500 records) containing seismic vulnerability functions, with the fields listed in Box K-3 and Box K-4.

K.16 Nationwide Weighted-Average Vulnerability Functions

Create a single set of weighted-average vulnerability functions, using total building areas from all states as weights. As before, to reflect recent trends in construction, weights only consider high-code building areas for states with high-code construction, moderate-code building areas for states without high-code construction, and low-code building areas for states without high or moderate-code construction. These are like those shown in Box K-3 and K-4 except:

MBTID: an integer 1000, to indicate a nationwide average
Model building type: "U.S."

Box K-4. Statewide Vulnerability Functions in Terms of 5% Damped 1-Sec Spectral Acceleration

MBTID: an integer 1xx, where xx denotes the state FIPS numeric code, as specified in "FIPS PUB" 5-2 (https://catalog.data.gov/dataset/fips-state-codes)
OCCID: an integer index 100 to indicate all residential occupancies, 200 to indicate all nonresidential occupancies, or 0 to indicate all occupancy classes
CSID: an integer index 1, 2, … 31 corresponding to a C_s value
IEID: an integer index 1, 2, … 10 corresponding to an I_e value
SA10ID: an integer index 0, 1, 2, … 400 corresponding to a value of SA10
Model building type: XX, where XX is the FIPS state alpha (same as postal) code as specified in FIPS PUB 5-2
Occupancy class: one of {RES, NRES, AVG}, indicating average of all residential occupancies, nonresidential occupancies, or all occupancies, 3 classes
C_s: one of $\{10^{-2}, 10^{-1.9}, \ldots 10^{1}\}$, units of gravity, 31 values
I_e: one of {1, 1.25, 1.5, 2, 3, 4, 5, 6, 7, 8}, 10 values
SA10: one of {0.00, 0.01, 0.02, … 4.00}, units of gravity, 401 values
$y_b(x)$ = mean building repair cost as a fraction of its replacement cost new given SA10 = x

…

(same as Box K-2)

...

$y_{tc}(x)$ = fraction of indoor occupants trapped in collapsed buildings, given SA10 = x

K.17 Uncertainty Does Not Matter to BCR

In Porter (2010), a method is proposed to model the uncertainty in loss when its expected value is calculated by the Hazus approach, but in the present case one does not need to calculate uncertainty. The EAL is solely a function of the expected value of loss at any level of excitation and the frequency with which that level of excitation is exceeded, as shown in Equation 4-1. That may seem counterintuitive. Recall however that EAL is the expected value of a sum of uncertain summands. The expected value of a sum equals the sum of the expected values of the summands. Put another way, the expected value operator E[*] is a linear operator, in the sense that

$$E[X + c] = E[X] + c$$
$$E[X + Y] = E[X] + E[Y]$$
$$E[aX] = aE[X]$$

where a and c are constants, X and Y are uncertain, and X need not be statistically independent of Y.

K.18 Calculating BCR at the Census-Tract, County, State, and National Level

The project team has extracted from Hazus a nationwide inventory of buildings, as discussed elsewhere in this Interim Study. The inventory estimates the stock of existing buildings, but one can extrapolate to new construction by recognizing that approximately 1% of the current building stock is replaced every year. Therefore, the benefits and costs of design are calculated to exceed I-Code requirements for 1% of the current building stock, which is the annual benefit and annual cost of designing to exceed I-Code requirements. The ratio of the benefit and cost is the BCR for exceeding I-Code requirements. The following defines the necessary parameters of hazard, vulnerability, and exposed value:

Hazard, from USGS National Seismic Hazard Maps

x = a particular value of SA02

G(x) = mean frequency (events per year) of earthquakes causing shaking SA02 ≥ x, by census tract

Vulnerability from Box K-3, from Sec K.1.15, by state, I_e value, and aggregate occupancy (RES or NRES)

A = total building area, 1000 sf, in a particular census tract and aggregate occupancy class (RES and NRES), as of some basis year, in the project team's case, 2002.

V_b = total replacement cost new of buildings in a census tract, by aggregate occupancy and basis year, $1000s

V_c = total replacement cost new of contents in a census tract, by aggregate occupancy class, and year, $1000s

N_{occ2PM} = total number of indoor occupants at 2 PM, by tract, aggregate occupancy class, etc., as of the basis year (2002)

N_{occ2AM} = number of indoor occupants at 2 AM, by tract, aggregate occupancy class, etc., as of the basis year (2002)

N_{occ5PM} = number of indoor occupants at 5 PM, by tract, aggregate occupancy class, etc., as of the basis year (2002)

N_{occ} = time-average number of indoor occupants, by tract, aggregate occupancy class, etc., as of the basis year (2002)

$$N_{occ} = \frac{40}{168} N_{occ2PM} + \frac{98}{168} N_{occ2AM} + \frac{30}{168} N_{occ5PM}$$

(Equation K-35)

I_A = estimated 2016 building area as a factor of building area in 2002 = 1.089, based on the ratio of U.S. population in the two years = 324,100,000/297,600,000

I_B = estimated 2016 square-foot construction cost as a factor of basis-year V_b, based on the ratio of RSMeans' 30-city average historical cost indices in 2016 and 2002, respectively = 1.61

V_{i1} = acceptable cost to avoid Hazus injury severity level 1 = $53,000

V_{i2} = acceptable cost to avoid Hazus injury severity level 2 = $550,000

V_{i3} = acceptable cost to avoid Hazus injury severity level 3 = $3,700,000

V_{i4} = acceptable cost to avoid Hazus injury severity level 4 = $9,500,000

V_{CRY} = acceptable cost to avoid collapse, red-tagging, or yellow-tagging. The project team cannot find sufficient evidence to assign a particular value to this parameter. This assumes that other calculations of loss associated with PTSD cover the emotional trauma associated with the sudden impairment of a home, and therefore assign V_{CRY} = $0.

V_{usar} = urban search and rescue cost to extricate 1 trapped victim = $10,000. It is based on 100 person-hours x $100/hr. The first figure is based on an estimated 2,000 person-hours expended in urban search and rescue efforts at the Northridge Meadows Apartment Buildings in the 1994 Northridge Earthquake, which extricated 20 people (https://goo.gl/C5CST6). The second figure is based on the annual budget of the Los Angeles Fire Department (approximately $630 million) divided by the number of uniformed firefighters (approximately 3200) divided by 2000 work hours per person per year.

g = population growth rate, U.S. average = 0.007 per year (World Bank 2017)

r = discount rate for private-sector or public-sector borrowing, less inflation. See Appendix H for discussion on values used.

t = duration over which benefits will be recognized. The half-life of a new building is probably on the order of 100 years, but the 2005 *Mitigation Saves* study recognized benefits only for 50 years in ordinary buildings. This uses an intermediate value of t = 75 years.

One then calculates, for each census tract and each aggregate occupancy (RES and NRES), the sum of A, V_b, V_c, N_{occ2AM}, N_{occ2PM}, N_{occ5PM}. Then calculate the following annualized damage and loss values for each set of I_e vulnerability functions. Use the vulnerability functions for the value of ASCE 7-10's C_s appropriate to each census tract, calculated as $2/3 \cdot S_{MS}/R$, where R is taken as 6.4, based on a building-value-weighted average for high-code (recent) California construction.

County (5-digit FIPS code, e.g., 06001 = Alameda County, CA)

Aggregated occupancy class (RES or NRES)

A = total building area, 1000 sf, in a particular census tract and aggregate occupancy class (RES and NRES), as of some basis year, in the project team's case, 2002.

V_b = total replacement cost new of buildings in a census tract, by aggregate occupancy and basis year, $1000s

V_c = total replacement cost new of contents in a census tract, by aggregate occupancy class, and year, $1000s

N_{occ2PM} = total number of indoor occupants at 2 PM, by tract, aggregate occupancy class, etc., as of the basis year (2002)

N_{occ2AM} = number of indoor occupants at 2 AM, by tract, aggregate occupancy class, etc., as of the basis year (2002)

N_{occ5PM} = number of indoor occupants at 5 PM, by tract, aggregate occupancy class, etc., as of the basis year (2002)

N_{occ} = time-average number of indoor occupants, by tract, aggregate occupancy class, etc., as of the basis year (2002)

EAD_b = expected annualized damage factor for building repairs, e.g., the expected value of the annual cost to repair new buildings, as a fraction of replacement cost new. (Note that this equation involves a proper integral that is actually evaluated numerically. The same form is used in many of the following equations. See Equation K-59 for the numerical method.)

$$EAD_b = \int_{x=0}^{\infty} y_b(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-36)

EAN_{i1} = expected annualized number of people in new buildings in Hazus injury severity 1. The factor I_A accounts for population growth. The factor 0.01 accounts for the fact that 1% of the existing building stock is added in a year. N_{occ} is number of people in 2002.

$$EAN_{i1} = I_A \cdot N_{occ} \cdot 0.01 \int_{x=0}^{\infty} y_{i1}(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-37)

EAN_{i2} = expected annualized number of people in new buildings in Hazus injury severity 2

$$EAN_{i2} = I_A \cdot N_{occ} \cdot 0.01 \cdot \int_{x=0}^{\infty} y_{i2}(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-38)

EAN_{i3} = expected annualized number of people in new buildings in Hazus injury severity 3

$$EAN_{i3} = I_A \cdot N_{occ} \cdot 0.01 \int_{x=0}^{\infty} y_{i3}(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-39)

EAN_{i4} = expected annualized number of people in new buildings in Hazus injury severity 4

$$EAN_{i4} = I_A \cdot N_{occ} \cdot 0.01 \cdot \int_{x=0}^{\infty} y_{i4}(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-40)

EAD_T = expected annualized number of days required to restore new buildings to functionality

$$EAD_T = \int_{x=0}^{\infty} y_T(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-41)

EAN_{dr} = expected annualized number of displaced households (RES only). The factor I_A accounts for population growth.

$$EAN_{dr} = I_A \cdot N_{occ2AM} \cdot \int_{x=0}^{\infty} y_T(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-42)

EAD_{col} = expected annualized fraction of new buildings experiencing collapse

$$EAD_{col} = \int_{x=0}^{\infty} y_{col}(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-43)

EAN_{col} = expected annualized number of new buildings experiencing collapse. In the following equation, the factor of 1,000 accounts for the fact that A is expressed in 1,000 sf. The factor of 0.01 accounts for the annual growth in the building stock.

$$EAN_{col} = I_A \cdot A \cdot 1000 \cdot 0.01 \cdot \int_{x=0}^{\infty} y_{COL}(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-44)

EAD_r = expected annualized fraction of new buildings that are red-tagged

$$EAD_r = \int_{x=0}^{\infty} y_r(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-45)

EAN_R = expected annualized number of new buildings that are red-tagged

$$EAN_R = I_A \cdot A \cdot 1000 \cdot 0.01 \cdot \int_{x=0}^{\infty} y_R(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-46)

EAD_y = expected annualized fraction of new buildings that are yellow-tagged

$$EAD_y = \int_{x=0}^{\infty} y_y(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-47)

EAN_Y = expected annualized number of new buildings that are yellow-tagged

$$EAN_Y = I_A \cdot A \cdot 1000 \cdot 0.01 \cdot \int_{x=0}^{\infty} y_Y(x$$

(Equation K-48)

EAN_{tc} = expected annualized number of occupants of new buildings who are trapped in collapsed buildings

$$EAN_{tc} = I_A \cdot N_{occ} \cdot 0.01 \cdot \int_{x=0}^{\infty} y_{tc}(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-49)

This then tabulates monetary losses in annualized terms:

EAL_b = expected annualized building repair cost of new buildings (all expressions for EAL are in 2016 USD). The factor of 0.01 is to account for the fact that only 1% of the building stock is replaced annually. The factor of 1000 accounts for the fact that V_c is expressed in $1000s.

$$EAL_b = EAD_b \cdot I_A \cdot I_B \cdot V_b \cdot 0.01 \cdot 1000$$

(Equation K-50)

EAL_c = expected annualized content repair cost in new buildings

$$EAL_c = I_A \cdot I_B \cdot V_c \cdot 0.01 \cdot 1000 \cdot \int_{x=0}^{\infty} y_c(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-51)

EAL_{tc} = expected annualized cost of urban search and rescue efforts.

$$EAL_{tc} = V_{usar} \cdot \left(EAN_{tc} + EAN_{i4} \right)$$

(Equation K-52)

EAL_{BI} = expected annualized loss associated with loss of function, both direct and indirect. The factor I_A adjusts the occupant loads N_{occ} from 2002 to 2017 values. The factor 0.01 accounts for the fact that 1% of the building stock is added or replaced annually. EAD_T is the average annual number of days that new buildings are unavailable. V_{BI} is the estimated output loss (the additional living expense or direct BI loss) in 2017 USD associated with one day's loss of use. The factor R_2 is a multiplier for indirect BI: it is the indirect BI loss calculated using input-output analysis resulting from $1.00 of direct BI. V_{BI} and R_2 vary by occupancy type and are shown in Table K-13.

$$EAL_{BI} = I_A \cdot \max\left(N_{occ2AM}, N_{occ2PM} \right) \cdot 0.01 \cdot EAD_T \cdot V_{BI} \cdot (1+Q)$$

(Equation K-53)

Now calculate acceptable costs to avoid statistical human injuries in expected annualized terms.

EAL_{i1} = expected annualized value of avoiding statistical Hazus severity 1 injuries

$$EAL_{i1} = EAN_{i1} \cdot V_{i1}$$

(Equation K-54)

EAL_{i2} = expected annualized value of avoiding statistical Hazus severity 2 injuries

$$EAL_{i2} = EAN_{i2} \cdot V_{i2}$$

(Equation K-55)

EAL_{i3} = expected annualized value of avoiding statistical Hazus severity 3 injuries

$$EAL_{i3} = EAN_{i3} \cdot V_{i3}$$

(Equation K-56)

EAL_{i4} = expected annualized value of avoiding statistical Hazus severity 4 injuries

$$EAL_{i4} = EAN_{i4} \cdot V_{i4}$$

(Equation K-57)

EAL_{PTSD} = expected annualized loss associated with PTSD, estimated as shown in Equation K-58, where V_{PTSD} = $90,000

$$EAL_{PTSD} = V_{PTSD} \cdot EAN_{i2}$$

(Equation K-58)

Several of these equations contain an integral of the form

$$I = \int_0^\infty y(x) \left| \frac{dG(x)}{dx} \right| dx$$

(Equation K-59)

Equation K-59 is only rarely solvable in closed form. More commonly, $y(x)$ and $G(x)$ are available at discrete values of x. If one has n+1 values of x, at which both $y(x)$ and $G(x)$ are available, and these are denoted by x_i, y_i, and G_i: $i = 0, 1, 2, \ldots n$, respectively, then I in Equation K-59 can be replaced by Equation K-60. The equation gives an exact solution when y(x) is linear between values of x and ln(G(x)) is linear between values of x:

$$I = \sum_{i=1}^{n} \left(y_{i-1} G_{i-1} \left(1 - \exp\left(m_i \Delta x_i\right)\right) - \frac{\Delta y_i}{\Delta x_i} G_{i-1} \left(\exp\left(m_i \Delta x_i\right) \left(\Delta x_i - \frac{1}{m_i} \right) + \frac{1}{m_i} \right) \right)$$

$$= \sum_{i=1}^{n} \left(y_{i-1} a_i - \Delta y_i b_i \right)$$

(Equation K-60)

Where,

$$\Delta x_i = x_i - x_{i-1} \qquad \Delta y_i = y_i - y_{i-1} \qquad m_i = \ln\left(G_i / G_{i-1}\right) / \Delta x_i \text{ for } i = 1, 2, \ldots n$$

$$a_i = G_{i-1}\left(1 - \exp\left(m_i \Delta x_i\right)\right) \qquad b_i = \frac{G_{i-1}}{\Delta x_i}\left(\exp\left(m_i \Delta x_i\right)\left(\Delta x_i - \frac{1}{m_i}\right) + \frac{1}{m_i}\right)$$

Porter (2016) shows several different ways how $I_e = 1.5$ costs approximately 1% greater construction cost than $I_e = 1.0$. In Equation K-61, one takes the marginal cost as proportional to the strength increase: 2% per unit of I_e above 1.0, with an additional factor of 0.01 to account for the 1% annual growth in the building stock. The benefit *b*, cost *c*, and BCR *bcr* of designing to exceed I-Code requirements for the given census tract, aggregate occupancy class (RES or NRES), and earthquake importance factor are given by

$$c = I_A \cdot I_B \cdot V_b \cdot 1000 \cdot 0.0002 \cdot \left(I_e - 1\right)$$

(Equation K-61)

$$PV_{Money} = \left(EAL_b + EAL_c + EAL_{BI} + EAL_{tc}\right) \cdot \left(\frac{\left(1 - \exp\left(-r \cdot t\right)\right)}{r}\right)$$

(Equation K-62)

$$PV_{Injuries} = \left(EAL_{i1} + EAL_{i2} + EAL_{i3} + EAL_{i4} + EAL_{PTSD}\right) \cdot t$$

(Equation K-63)

$$PV = PV_{Money} + PV_{Injuries}$$

(Equation K-64)

$$b = PV_{I_e = 1.0} - PV_{I_e > 1.0}$$

(Equation K-65)

In Equations K-62 and K-63, money refers to losses associated with financial consequences while injuries refers to losses associated with deaths and nonfatal injuries, including PTSD. Evaluate Equations K-61 through K-65 for each census tract, each aggregate occupancy class, and each value of $I_e \in \{1.0, 1.25, 1.5, 2.0, \ldots 8.0\}$. As discussed earlier, this does not apply a discount rate to statistical injuries avoided.

K.19 Aggregation to Counties

Readers of the *2017 Interim Report* may have trouble digesting BCR information at the census-tract level. Few people know what census tract their buildings are in. Therefore, benefits and costs are aggregated first at the county and then at the state level. Census tract numbers contain within them a code to indicate its state (the first 2 digits) and county (the next 3 digits). Thus, the first 5 digits uniquely identify a county and state. Therefore, sum benefits and costs over all tracts for each combination of:

- County FIPS code (first 5 digits of the census tract number)
- I_e value, and
- Aggregate occupancy class (RES or NRES).

This assumes a fraction *f* of all new buildings are designed to exceed I-Code requirements, and initially take *f* as 1.0. Results can later be scaled by whatever fraction *f* seems realistic. The quantity BCR is insensitive to *f*.

$$B_{County} = f \cdot \sum_{tracts} b$$

(Equation K-66)

$$C_{County} = f \cdot \sum_{tracts} c$$

(Equation K-67)

$$BCR_{County} = \frac{B_{County}}{C_{County}}$$

(Equation K-68)

Again, evaluate Equations K-64 through K-66 for each value of $z \in \{1.25, 1.5, 2.0, \ldots 8.0\}$, searching for the range of I_e (e.g., the particular values of z) where BCR > 1.0. Note that if the same fraction of new buildings are designed to exceed I-Code requirements in each subsequent year 0, 1, 2, ... t-1, benefits and costs will increase with population growth as in:

$$\begin{aligned}\hat{B}_{County} &= B_{County} \cdot \sum_{n=0}^{t-1} (1+p)^n \\ &= B_{County} \cdot P\end{aligned}$$

(Equation K-69)

$$\begin{aligned}\hat{C}_{County} &= C_{County} \cdot \sum_{n=0}^{t-1} (1+p)^n \\ &= C_{County} \cdot P\end{aligned}$$

(Equation K-70)

For the given values of population growth rate p = 0.007/year and t = 75 years, P = 98.2. BCR remains as calculated in Equation K-68.

Thus, one evaluates Equations K-69 and K-70 for each combination of county FIPS code, aggregate occupancy class (RES or NRES), and each I_e value above 1.0, e.g., z ∈ {1.25, 1.5, 2.0, … 8.0}.

One also calculates total BCR by county:

$$BCR_{TOT} = \frac{B_{RES} + B_{NRES}}{C_{RES} + C_{NRES}}$$

(Equation K-71)

K.20 Aggregation to State Level

The first two digits of the 5-digit county FIPS code uniquely identify the state, so repeat Equations K-71 through K-73 aggregating benefits and costs for each unique combination of 2-digit state FIPS code, aggregate occupancy class (RES or NRES), and each I_e value above 1.0, e.g., $z \in$ {1.25, 1.5, 2.0, … 8.0}. Also calculate statewide aggregate BCR as

$$B_{State} = \sum_{Counties} B_{County}$$

(Equation K-72)

$$C_{State} = \sum_{Counties} C_{County}$$

(Equation K-73)

$$BCR_{State} = \frac{B_{State}}{C_{State}}$$

(Equation K-74)

K.21 IEMax I_e Value

The analyst is interested in the point of diminishing returns: the level of I_e at which an increase in I_e raises costs more than it raises benefits. This refers to that value as the IEMax I_e. Let:

i = index to I_e values: i = 0 refers to I_e = 1.0, i = 1 refers to I_e = 1.25, i = 2 refers to I_e = 1.5, etc.
$I_{e,i}$ = I_e value associated with index i
B_i = statewide benefit associated with the i^{th} value of I_e. For example, B_3 denotes the statewide benefit associated with I_e = 2.0.
C_i = statewide cost associated with the i^{th} value of I_e.

$$\Delta B_i = B_i - B_{i-1} \qquad i > 0$$

(Equation K-75)

$$\Delta C_i = C_i - C_{i-1} \qquad i > 0$$

(Equation K-76)

$$\hat{I}_e = I_{e,i} \quad \max\{i\} : \frac{\Delta B_i}{\Delta C_i} \geq 1.0$$

(Equation K-77)

Equation K-77 gives the IEMax value of I_e.

K.22 Sensitivity Tests

1. Discount rate = 3%

This is one of two standard discount rates used by the OMB:

$r_{RES} = r_{NRES} = 0.03$

2. Discount rate = 7%, the other OMB discount rate:

$r_{RES} = r_{NRES} = 0.07$

3. Collapse probability at MCE_R = 2%

Perhaps, in contrast with the evidence in FEMA P-695 (2009c) discussed in Porter (2015), the average collapse probability of new buildings subjected to MCE_R shaking is as low as $P_c = 0.02$ (R. Hamburger written communication, 9 Jun 2017). The lower collapse probability at MCE_R would affect the collapse fragility function and everything that depends on collapse fragility, especially number of collapsed buildings, number of red-tagged buildings, and number of yellow-tagged buildings.

These are recalculated by changing the median collapse capacity values in Section K.1.10, then by recalculating everything that comes after. This uses the definitions of C_S and R offered in Section K.1.10, and denoted by β the standard deviation of the natural logarithm of collapse capacity. Luco et al. (2007) use β = 0.8. One can estimate the median capacities of Equations K-25 and K-26 by substituting these quantities into:

$\theta = 1.5 \cdot C_S \cdot R \cdot \exp(-\Phi^{-1}(P_c) \cdot \beta)$

Which would imply the following alternatives to Equation K-25 and K-26:

$\theta_{02} = 7.76 \cdot C_S \cdot R \cdot I_e$ for low-rise buildings (1-3 stories)

$\theta_{10} = 7.76 \cdot C_S \cdot R \cdot I_e$ for mid- and high-rise buildings (4+ stories),

Appendix L. Project Participants

The MMC Board wishes to acknowledge the efforts of its subcontractor, SPA Risk LLC, and the project participants, as follows.

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Natalie Peyronnin, Environmental Defense Fund, Washington, DC
Evan Reis, U.S. Resiliency Council, San Francisco, CA
Audrey Rierson, Federal Alliance for Safe Homes, Tallahassee, FL
Julie Rochman, Insurance Institute for Business & Home Safety, Tampa, FL

Dominic Sims, International Code Council, Washington, DC
Ryan Smith, Economic Development Administration, U.S. Department of Commerce, Washington, DC
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General
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Edward Laatsch, FEMA HQ
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Appendix M. Specific Summaries of Results

This Appendix offers a recap of the most important findings from this Interim Study via a series of one-page summaries that are targeted to various different audiences. The summaries focus on the following findings:

- Overall Summary of Results
- Reduction in deaths, injuries, and instances of PTSD and job creation
- Benefits and costs of federally-supported grants to mitigate public-sector risk resulting from:
  - Riverine Flood
  - Wind
  - Earthquake
  - Fire at the WUI
- Benefits and costs of designing to exceed I-Code requirements for new buildings to reduce risk resulting from:
  - Riverine flood
  - Hurricane surge
  - Hurricane winds
  - Earthquake
  - Fire at the WUI

The Interim Study results can be used to fulfill the specific needs of numerous stakeholder groups. The remaining one-page summaries provide insight into these potential uses.

- Architects can reference the *2017 Mitigation Saves Interim Report* to inform early conversations with clients about project goals and the potential value of mitigation.
- Structural engineers need information about the up-front costs and financial benefits mitigation during retrofit and new design.
- Participants in building code development can reference the *2017 Mitigation Saves Interim Report* to inform code development.
- Educators and trainers in disaster risk reduction can reference the *2017 Mitigation Saves Interim Report* to inform educational curriculum.

National Institute of BUILDING SCIENCES

Mitigation Saves:

Federal Grants Provide $6 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study*,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Federal Grant Programs

Considering the subtotal for the past 23 years of federally funded natural hazard mitigation, at the cost-of-borrowing discount rate, the analysis suggests that society will ultimately save $6 for every $1 spent on up-front mitigation cost. The past 23 years of federally funded natural hazard mitigation is estimated to prevent deaths, nonfatal injuries and PTSD worth $68 billion, equivalent to approximately 1 million nonfatal injuries, 600 deaths and 4,000 cases of PTSD. Table 1 provides benefit-cost ratios (BCRs) for each natural hazard the project team examined. Figure 1 shows the contributions to the calculation of these benefits.

The federal agency strategies consider 23 years of public sector mitigation of buildings funded through FEMA programs including the Flood Mitigation Assistance Grant Program (FMA), Hazard Mitigation Grant Program (HMGP), Public Assistance Program (PA) and Pre-Disaster Mitigation Grant Program (PDM), plus the HUD Community Development Block Grant Program (CDBG) and several programs of the EDA. Barring identification of additional federal data sets or sources of federal mitigation grant and loan funding, these analyses represent essentially the complete picture of such mitigation measures. In the future, the project team might also look at mitigation measures directly implemented by federal agencies.[1] Results represent an enhanced and updated analysis of the mitigation measures covered in the 2005 study. Public-sector mitigation strategies include:

- For flood resistance, acquire or demolish flood-prone buildings, especially single-family dwellings, manufactured homes and 2- to 4-family dwellings.
- For wind resistance, add shutters, safe rooms and other common measures.
- For earthquake resistance, strengthen various structural and nonstructural components.
- For fire resistance, replace roofs, manage vegetation to reduce fuels and replace wooden water tanks.

[1]Such measures include U.S. Army Corp of Engineers levees and other water management programs; National Oceanic and Atmospheric Administration early warning systems for weather; and U.S. Department of Agriculture (USDA) Forest Service prescribed burns.

Mitigation Saves: Federal Grants Provide $6 Benefit for Each $1 Invested

The national-level BCRs aggregate study findings across natural hazards and across state and local BCRs. The *Interim Study* examined four specific natural hazards: riverine and coastal flooding, hurricanes, earthquakes and fires at the wildland-urban interface (WUI). Discussion of each hazard and the associated BCRs are provided in separate summaries.

Natural Hazard Mitigation Saves in Every State

Every state in the contiguous United States is estimated to experience at least $10 million in benefits from federal grants to mitigate flood, wind, earthquake, or fire at the wildland-urban interface. The majority of states enjoy at least $1 billion in benefits. Four states—Louisiana, New Jersey, New York and Texas—enjoy at least $10 billion in benefits. See Figure 2.

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	6:1	4:1
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

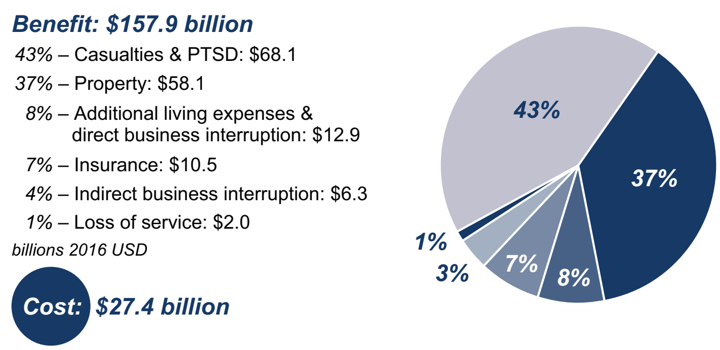

Figure 1. Total costs and benefits of 23 years of federal mitigation grants.

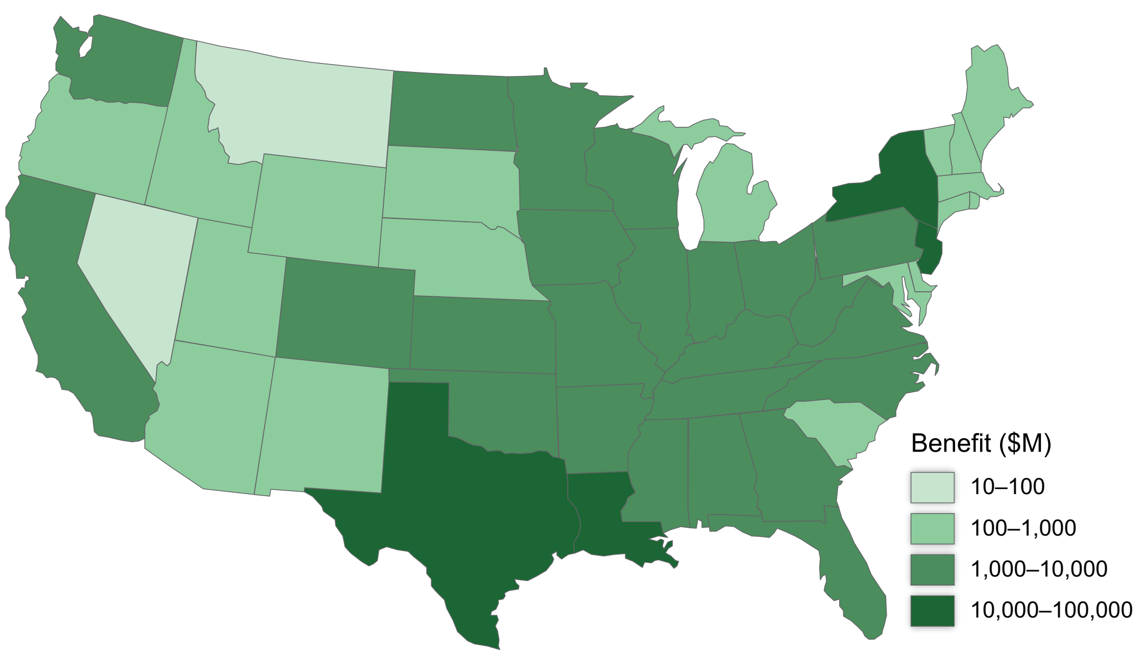

Figure 2. Aggregate benefit by state from federal grants for flood, wind, earthquake, and fire mitigation.

National Institute of
BUILDING SCIENCES

Mitigation Saves:

For Riverine Flood Mitigation, Federal Grants Provide $7 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study*,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Federal Grants for Flood Mitigation

The public-sector mitigation strategy examined for flood resistance is the acquisition or demolition of flood-prone buildings, especially single-family dwellings, manufactured homes, and 2- to 4-family dwellings. While the benefit-cost ratio (BCR) varies across projects, public-sector mitigation spending for the acquisition of buildings exposed to riverine flooding appears to be cost-effective. The average BCR across the sample projects is approximately 7:1. The implication is that past federally funded riverine flood mitigation is cost-effective (at the cost-of-borrowing discount rate). Given that the total cost of all riverine flood-mitigation grants was $11.5 billion, a BCR of 7:1 implies that federally funded flood mitigation will ultimately save the United States $82 billion. Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the benefits specifically attributable to federal flood mitigation grants. The national-level BCRs aggregate study findings across natural hazards and across state and local BCRs.

Mitigation Saves: For Riverine Flood Mitigation, Federal Grants Provide $7 Benefit for Each $1 Invested

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	**6:1**	**4:1**
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

Benefit: $82 billion

65% – Property: $53.0

12% – Additional living expenses & sheltering: $10.0

11% – Insurance: $9.0

6% – Casualties & PTSD: $5.0

6% – Indirect business interruption: $5.0

billions 2016 USD

Cost: $11.5 billion

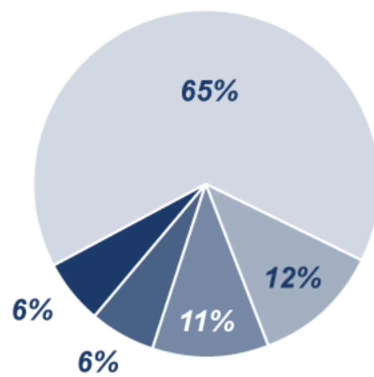

Figure 1. Contribution to benefit from federally funded riverine flood grants.

National Institute of BUILDING SCIENCES

Mitigation Saves:

For Wind Mitigation, Federal Grants Provide $5 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study, the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Federal Grants for Wind Mitigation

Federal grants to mitigate wind damage are highly cost-effective. In 23 years, public entities have spent $13.6 billion to mitigate future wind losses; these efforts will ultimately save the United States an estimated $70 billion in avoided property losses, additional living expenses, business impacts, and deaths, injuries, and post-traumatic stress disorder (PTSD). Their total benefit-cost ratio (BCR) is approximately 5:1.

For wind resistance the mitigation measures examined include the addition of shutters, safe rooms, and other common measures. Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the benefits specifically attributable to federal flood mitigation grants. The national-level BCRs aggregate study findings across natural hazards and across state and local BCRs.

The estimated BCR depends largely on the level of hazard, alternative use of the facility, and accessibility. In-home safe rooms generally appear to be cost-effective, exhibiting an average BCR of 4.25. Large facilities with dual purposes, such as school gymnasia and cafeterias, exhibit an average BCR of 8.0. In these cases, the cost of mitigation is simply the additional cost of hardening the facility.

Accessibility and use also strongly affect cost-effectiveness. For example, a shelter located at a hospital will likely protect life at any time of day throughout the year. Shutters appear to be highly cost-effective, particularly those that protect valuable equipment at utilities or industrial facilities. Shutters for ordinary public buildings without high-value contents produce a lower but still impressive BCR (about 3.5).

Mitigation Saves: For Wind Mitigation, Federal Grants Provide $5 Benefit for Each $1 Invested

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	**6:1**	**4:1**
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

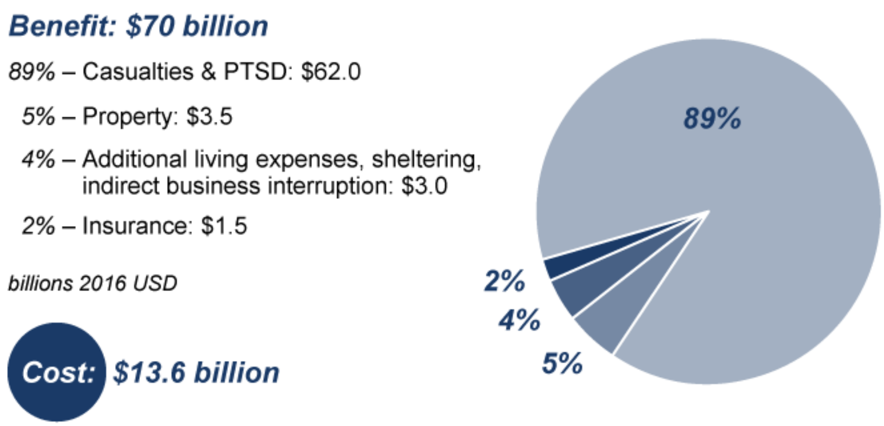

Figure 1. Contribution to benefit from federally funded wind grants.

National Institute of BUILDING SCIENCES

Mitigation Saves:

For Earthquake Mitigation, Federal Grants Provide $3 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study*,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Federal Grants for Earthquake Mitigation

Considering mitigation costs totaling $2.2 billion, the average benefit-cost ratio (BCR) of approximately $3 to $1 implies that federally funded earthquake hazard mitigation between 1993 and 2016 saves society $5.7 billion.

For earthquake resistance the mitigation measures examined include strengthening various structural and nonstructural components. Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the benefits specifically attributable to federal earthquake mitigation grants. The national-level BCRs aggregate study findings across natural hazards and across state and local BCRs.

As with the 2005 study, property benefits alone do not equal mitigation cost, but the sum of property and casualties do. By adding other societal benefits—business interruption losses and especially loss of service to society—earthquake mitigation more than pays for itself. That observation reinforces the notion that earthquake risk mitigation broadly benefits society. That is, strengthen one building and the benefits extend far beyond the property line: to the families of the people who work in the building and to the community that the building serves.

Mitigation Saves: For Earthquake Mitigation, Federal Grants Provide $3 Benefit for Each $1 Invested

National Benefit-Cost Ratio Per Peril
**BCR numbers in this study have been rounded*

	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	**6:1**	**4:1**
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

Benefit: $5.7 billion

34% – Loss of service: $1,900

26% – Property: $1,500

19% – Casualties: $1,100

16% – Direct business interruption: $900

5% – Indirect business interruption: $300

millions 2016 USD

Cost: $2.2 billion

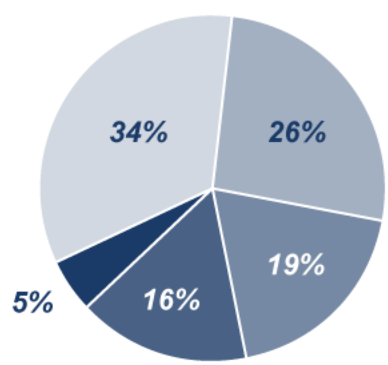

Figure 1. Contribution to benefit from federally funded earthquake mitigation grants.

Mitigation Saves:

At the Wildland Urban Interface, Federal Grants for Mitigation of Fire Provide $3 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study*,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Federal Grants for Earthquake Mitigation

With a total project cost of approximately $56 million (inflated to 2016 USD), federally supported mitigation of fire at the wildland-urban interface (WUI) will save society an estimated $173 million in avoided future losses. For the 25 grants with sufficient data, the analysis produced an average benefit-cost ratio (BCR) of approximately 3:1.

For WUI fire resistance the mitigation measures examined include replacing roofs, managing vegetation to reduce fuels, and replacing wooden water tanks. Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the benefits specifically attributable to federal wildland fire mitigation grants. The national-level BCRs aggregate study findings across natural hazards and across state and local BCRs.

Mitigation Saves: At the Wildland Urban Interface, Federal Grants for Mitigation of Fire Provide $3 Benefit for Each $1 Invested

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	**6:1**	**4:1**
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

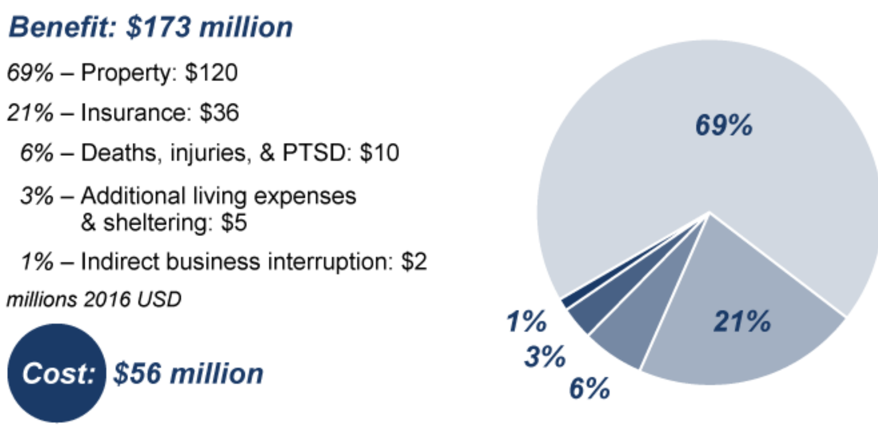

Figure 1. Contribution to benefit from federally funded WUI fire mitigation grants.

Mitigation Saves:

Designing to Exceed 2015 Codes Provides $4 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study, the project team analyzed two areas of mitigation programs:

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- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Exceeding Code

If all new buildings were built to the incrementally efficient maximum (IEMax) design to exceed select requirements of the 2015 IBC and IRC and compliance with the 2015 IWUIC for one year, new construction would save approximately $4 in avoided future losses for every $1 spent on additional, up-front construction cost. Such measures are estimated to prevent approximately 32,000 nonfatal injuries, 20 deaths and 100 cases of PTSD.

Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the overall ratio of costs to benefits for the design of new buildings to exceed the select I-Code requirements that the project team studied. The costs reflect only the added cost relative to the 2015 IBC and IRC. Where communities have an older code or no code in place, additional costs and benefits will accrue. If all new buildings built the year after were also designed to exceed select I-Code requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

The stringency of codes adopted at the state and local level varies widely. The project team used the unamended 2015 IBC and IRC as the baseline minimum codes for this study. Minimum codes provide a significant level of safety, however, society can save more by designing some new buildings to exceed minimum requirements of the 2015 Codes. Strategies to exceed minimum requirements of the 2015 Codes studied here include:

- For flood resistance (to address riverine flooding and hurricane surge), build new homes higher above base flood elevation (BFE) than required by the 2015 IBC.
- For resistance to hurricane winds, build new homes to comply with the Insurance Institute for Business

& Home Safety (IBHS) FORTIFIED Home Hurricane standards.

- For resistance to earthquakes, build new buildings stronger and stiffer than required by the 2015 IBC.
- For fire resistance in the wildland-urban interface, build new buildings to comply with the 2015 IWUIC.

The national-level BCRs aggregate study findings across natural hazards and across state and local BCRs. The *Interim Study* examined four specific natural hazards: riverine and coastal flooding, hurricanes, earthquakes and fires at the wildland-urban interface (WUI). Discussion of each hazard and the associated BCRs are provided in separate summaries.

All Stakeholders Benefit from Mitigation Investments

All major stakeholder groups, including developers, title holders, lenders, tenants and the community, enjoy net benefits from new design to exceed the code requirements studied. See Figure 2. All of society wins when builders make new buildings meet an IEMax level of design exceeding 2015 I-Code requirements where it makes financial sense, on a societal level, to do so. The benefits to tenants and owners only accrue to those who own or occupy buildings designed to exceed 2015 I-Code requirements, not for example to the people who live or work in buildings not designed to exceed I-Code requirements. However, even those who do not own or occupy those buildings enjoy a share of the community benefits.

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	6:1	4:1
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Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

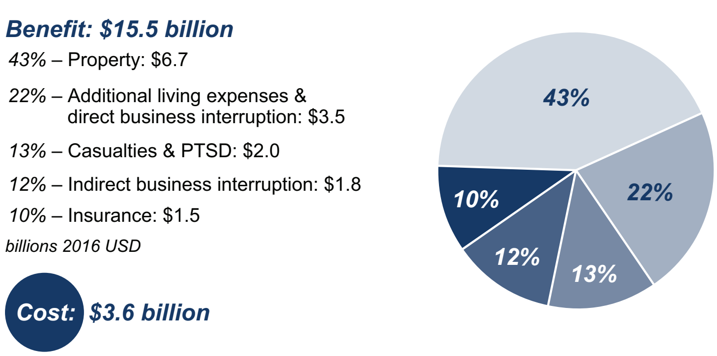


Figure 1. Total costs and benefits of new design to exceed 2015 I-Code requirements.

Figure 2. Stakeholder net benefits resulting from one year of constructing all new buildings to exceed select 2015 IBC and IRC requirements or to comply with 2015 IWUIC.

National Institute of BUILDING SCIENCES

Mitigation Saves:

For Riverine Flooding, Designing to Exceed 2015 Codes Provides $5 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the *2017 Interim Study,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Exceeding Code for Riverine Flooding

The cost to build all new buildings 5 feet above the base flood elevation (BFE) for one year is approximately $900 million. This would produce approximately $4.2 billion in benefits, for an aggregate benefit-cost ratio (BCR) of approximately 5:1, e.g., $5 saved for every $1 spent to build new buildings higher out of the flood-plain.

Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the overall ratio of costs to benefits for the design of new buildings to exceed riverine flooding requirements of the 2015 IBC. The strategy to exceed minimum requirements of the 2015 Codes for riverine flooding is to build new buildings in the 1% annual chance floodplain higher above base flood elevation (BFE) than required by the 2015 IBC. The project team aggregated state and local BCRs to determine the national-level BCR. The costs reflect only the added cost relative to the 2015 IBC.

The stringency of codes adopted at the state and local level varies widely. The project team used the unamended 2015 IBC and IRC as the baseline minimum codes for this study. While minimum codes provide a significant level of safety, society can save more by designing some new buildings to exceed minimum requirements of the 2015 Codes. Where communities have an older code or no code in place, additional costs and benefits will accrue. If all new buildings built the year after were also designed to exceed select I-Code requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

Mitigation Saves: For Riverine Flooding, Designing to Exceed 2015 Codes Provides $5 Benefit for Each $1 Invested

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	**6:1**	**4:1**
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

Benefit: $15.5 billion

43% – Property: $6.7

22% – Additional living expenses & direct business interruption: $3.5

13% – Casualties & PTSD: $2.0

12% – Indirect business interruption: $1.8

10% – Insurance: $1.5

billions 2016 USD

Cost: ***$3.6 billion***

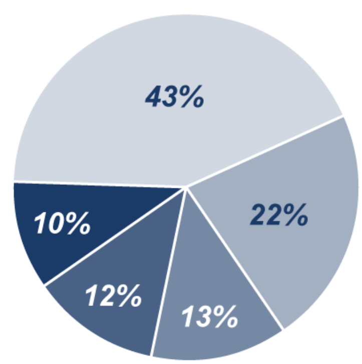


Figure 1. Nationwide benefits by category for designing to exceed 2015 I-Code requirements for flood.

Mitigation Saves:

For Hurricane Surge, Designing to Exceed 2015 Codes Provides $7 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the *2017 Interim Study,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested..
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Exceeding Code for Hurricane Surge

Building new single-family dwellings higher above the base flood elevation (BFE) than the 1-foot required by the 2015 IRC appears to be cost-effective in coastal surge areas identified as V or VE by FEMA in all states. Surge in coastal V-zones is different from riverine flooding, and so its costs and benefits are different.

When the incrementally efficient maximum (IEMax) increase in building height is assessed on a state level, the aggregate BCR (summing benefits and costs over all states) is approximately 7:1, e.g., $7 saved for every $1 spent to build new coastal buildings in V- and VE-zones higher above the shoreline. It would cost approximately $7 million extra to build all new buildings to the IEMax elevation above BFE for one year, and would produce approximately $51 million in benefits.

Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the overall ratio of costs to benefits for the design of new buildings to exceed hurricane related coastal flooding requirements of the 2015 IRC. The IEMax additional height varies by state, as illustrated in Table 2. The results strongly suggest that greater elevation of new coastal single-family dwellings in V-zones is widely cost-effective. All states have an IEMax building height above code of at least 5 feet. These costs and benefits refer to building new coastal single-family dwellings higher above BFE, not of elevating existing houses. The project team aggregated state and local BCRs to determine the national-level BCR. The costs reflect only the added cost relative to the 2015 IRC.

Mitigation Saves: For Hurricane Surge, Designing to Exceed 2015 Codes Provides $7 Benefit for Each $1 Invested

The stringency of codes adopted at the state and local level varies widely. The project team used the unamended 2015 IBC and IRC as the baseline minimum codes for this study. While minimum codes provide a significant level of safety, society can save more by designing some new buildings to exceed minimum requirements of the 2015 Codes. Where communities have an older code or no code in place, additional costs and benefits will accrue. If all new buildings built the year after were also designed to exceed select I-Code requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
Overall Hazard Benefit-Cost Ratio	**6:1**	**4:1**
Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

Benefit: $51 million

68% – Property: $35.0

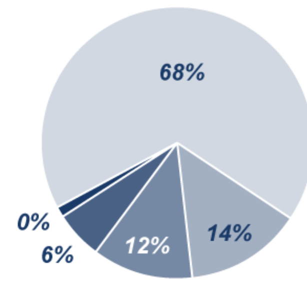
14% – Living expenses, sheltering: $7.0

12% – Insurance: $6.0

6% – Indirect business interruption: $3.0

0% – Casualties & PTSD: $0.2

millions 2016 USD



Cost:* *$7 million

Figure 1. Nationwide benefits by category for designing to exceed 2015 I-Code requirements for flood.

State	First Floor Height above BFE up to IEMax	BCR
Texas	+2 to 8	**20.2** to **9.1**
Louisiana	+2 to 10	**11.3** to **4.8**
Mississippi	+2 to 10	**27.6** to **10.1**
Alabama	+2 to 10	**31.1** to **11.7**
Florida	+2 to 10	**21.1** to **8.4**
Georgia	+2 to 6	**6.7** to **3.8**
South Carolina	+2 to 10	**11.8** to **5.0**
North Carolina	+2 to 10	**12.6** to **5.2**
Virginia	+2 to 6	**6.7** to **3.8**
Delaware	+2 to 6	**6.7** to **3.8**
Maryland	+2 to 6	**6.7** to **3.8**
New Jersey	+2 to 6	**6.7** to **3.8**
New York	+2 to 6	**6.7** to **3.8**
Connecticut	+2 to 6	**6.7** to **3.8**
Rhode Island	+2 to 6	**6.7** to **3.8**
Massachusetts	+2 to 6	**6.9** to **3.9**
Total		**16.9** to **7**

Table 2. BCRs for various heights above BFE for new coastal V-zone buildings up to the point where the incremental benefit remains cost-effective.

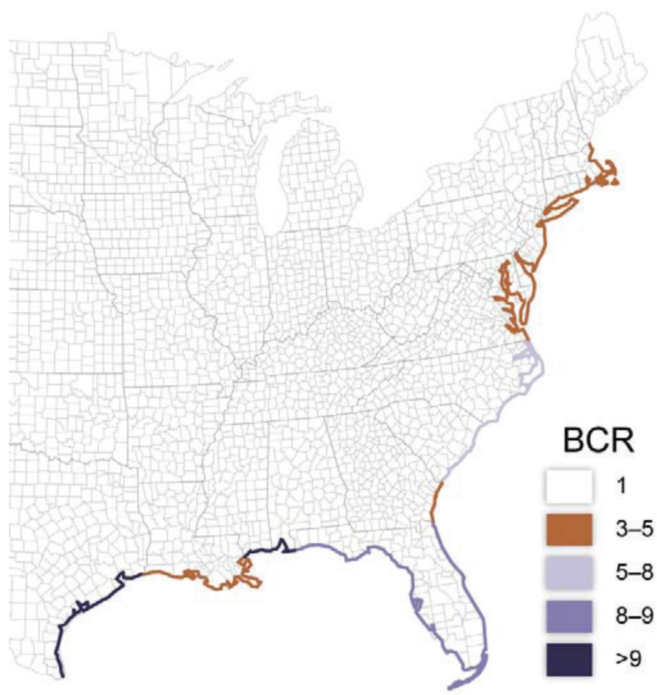


Figure 2: BCR of coastal flooding mitigation by elevating homes above 2015 IRC requirements (by state).

For Hurricane Winds, Designing to Exceed 2015 Codes Provides $5 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study*,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Exceeding Code for Hurricane Surge

If all new homes were built to the incrementally efficient maximum (IEMax) Insurance Institute for Business and Home Safety (IBHS) FORTIFIED Home program level for 1 year, it would cost approximately $720 million extra and would produce approximately $3.8 billion in avoided future losses. The aggregate benefit-cost ratio (BCR) (summing benefits and costs over all states) is approximately 5:1, e.g., $5 saved for every $1 spent to build new buildings better along the Gulf and Atlantic Coasts.

Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the overall ratio of costs to benefits for the design of new buildings to exceed hurricane related coastal flooding requirements of the 2015 IRC. Compliance with the IBHS FORTIFIED Home Hurricane program appears to be cost-effective everywhere along the Atlantic and Gulf Coast. The IEMax FORTIFIED level varies by state, as illustrated in Figure 2. The project team aggregated state and local BCRs to determine the national-level BCR. The costs reflect only the added cost relative to the 2015 IRC.

The stringency of codes adopted at the state and local level varies widely. The project team used the unamended 2015 IBC and IRC as the baseline minimum codes for this study. While minimum codes provide a significant level of safety, society can save more by designing some new buildings to exceed minimum requirements of the 2015 Codes. Where communities have an older code or no code in place, additional costs and benefits will accrue. If all new buildings built the year after were also designed to exceed select I-Code requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

Mitigation Saves: For Hurricane Winds, Designing to Exceed 2015 Codes Provides $5 Benefit for Each $1 Invested

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
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Riverine Flood	7:1	5:1
Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

Benefit: $3.8 billion

39% – Building and contents: $1,500

29% – Living expenses: $1,100

16% – Insurance: $600

16% – Indirect business interruption: $600

millions 2016 USD

Cost: $720 million

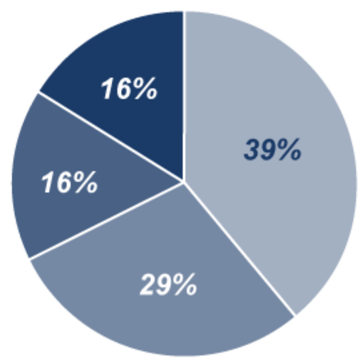

Figure 1. Benefits and costs for 1 year of new construction at the IEMax IBHS FORTIFIED Home Hurricane levels.

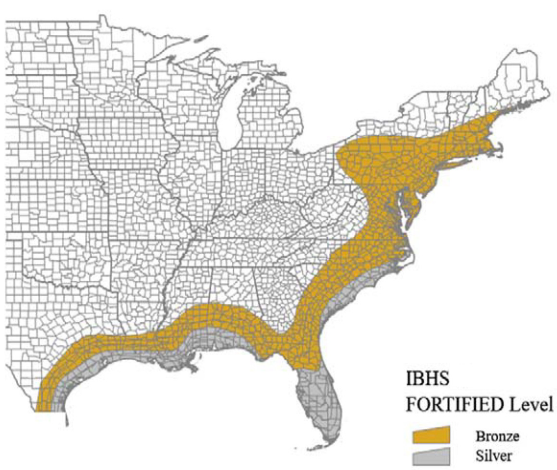

Figure 2. Maximum level of the IBHS FORTIFIED Home Hurricane design for new construction where the incremental benefit remains cost-effective.

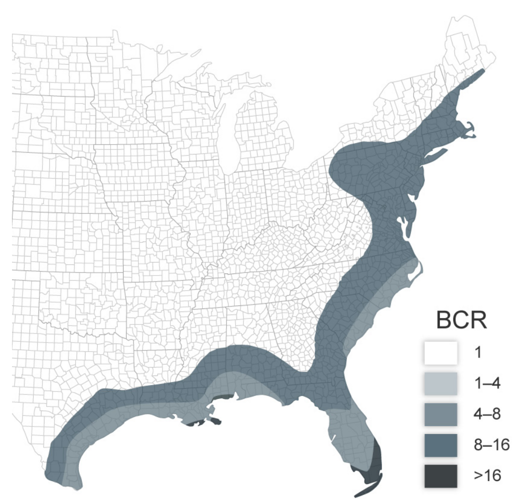

Figure 3: BCR of hurricane wind mitigation by building new homes under the FORTIFIED Home Hurricane Program (by wind band).

National Institute of BUILDING SCIENCES

Mitigation Saves:

For Earthquakes, Designing to Exceed 2015 Codes Provides $4 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study*,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Exceeding Code for Earthquakes

Considering just counties where design to exceed 2015 I-Code requirements for earthquakes has a benefit-cost ratio (BCR) greater than 1.0, if all new buildings were built to their county's incrementally efficient maximum (IEMax) level of strength and stiffness for one year the costs would total approximately $1.2 billion. The sum of the benefits totals approximately $4.3 billion. Therefore, the overall average BCR is approximately 4:1, e.g., an average of $4 saved for every $1 spent to build new buildings stronger and stiffer.

Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the overall ratio of costs to benefits for the design of new buildings to exceed earthquake design requirements of the 2015 IBC. The IEMax strength and stiffness for approximately 2,700 counties (from a BCR perspective) is 1.0, e.g., current code minimum. For approximately 400 counties however, design to exceed 2015 I-Code earthquake requirements appears to be cost-effective. Approximately 40 million people, 13% of the 2010 population of the U.S., live in counties where the IEMax strength and stiffness is twice the code minimum. Another 30 million people—10% of the United States population—live where it would be cost-effective to design to 25% or 50% greater than code-minimum strength and stiffness. The current code makes economic sense on a benefit-cost basis for about three-quarters of the United States population. The IEMax strength and stiffness by county is illustrated in Figure 2. The national-level BCRs aggregate study findings across state and local BCRs. The costs reflect only the added cost relative to the 2015 IBC.

Mitigation Saves: For Earthquakes, Designing to Exceed 2015 Codes Provides $4 Benefit for Each $1 Invested

The stringency of codes adopted at the state and local level varies widely. The project team used the unamended 2015 IBC and IRC as the baseline minimum codes for this study. While minimum codes provide a significant level of safety, society can save more by designing some new buildings to exceed minimum requirements of the 2015 Codes. Where communities have an older code or no code in place, additional costs and benefits will accrue. If all new buildings built the year after were also designed to exceed select I-Code requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
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Hurricane Surge	Too few grants	7:1
Wind	5:1	5:1
Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

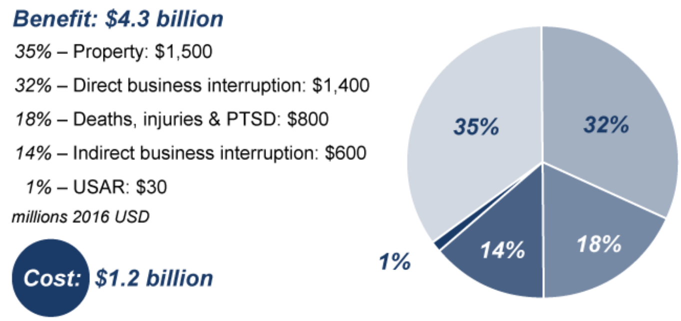

Figure 1. Contribution to benefits from exceeding 2015 I-Code earthquake requirements.

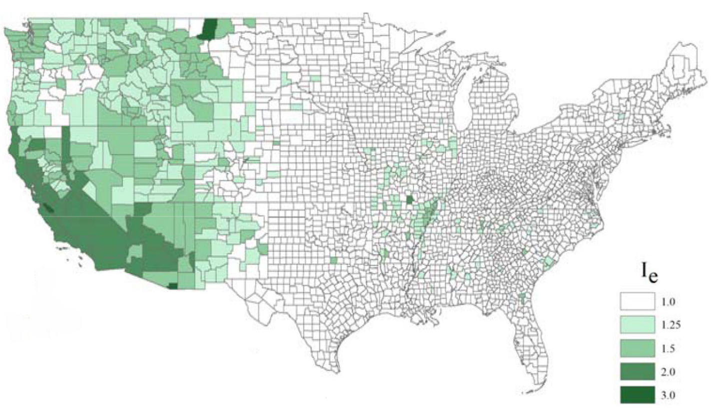

Figure 2. Maximum strength and stiffness factor Ie to exceed 2015 IBC and IRC seismic design requirements where the incremental benefit remains cost-effective.

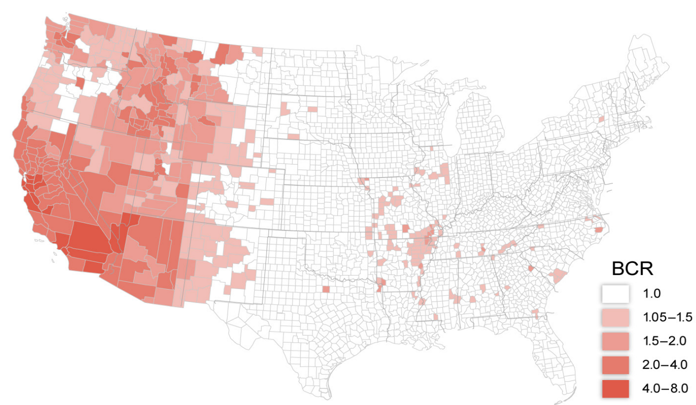

Figure 3. BCR of earthquake mitigation by increasing strength and stiffness in new buildings (by county).

National Institute of BUILDING SCIENCES

Mitigation Saves:

At the Wildland Urban Interface, Complying with the 2015 IWUIC Provides $4 Benefit for Each $1 Invested

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

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- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Results of Compliance with the IWUIC

If all new buildings built in one year in census blocks with a benefit-cost ratio (BCR) over 1 complied with the 2015 IWUIC, compliance would add about $800 million to total construction cost for that year. The present value of benefits would total approximately $3.0 billion, suggesting a BCR of approximately 4:1, e.g., $4 saved for every $1 of additional construction and maintenance cost.

Table 1 provides BCRs for each natural hazard the project team examined. Figure 1 shows the overall ratio of costs to benefits for the design of new buildings to comply with requirements of the 2015 IWIUC. The BCR only exceeds 1.0 where the fire risk is moderate or higher. Of the 47,870 census blocks, about 10,000 of them (21%) have a BCR greater than 1.0. About 10.5% have BCR > 2.6. About 2% have BCR > 8, and the highest BCR is 15.3. Figure 2 provides the BCR by county. The project team aggregated state and local BCRs to determine the national-level BCR.

If all new buildings built the year after were also designed to meet IWUIC requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

Mitigation Saves: At the Wildland Urban Interface, Complying with the 2015 IWUIC Provides $4 Benefit for Each $1 Invested

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Earthquake	3:1	4:1
Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

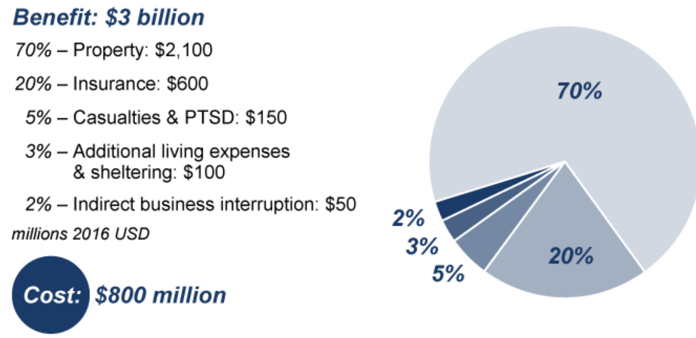

Figure 1. Contribution to benefits from 1 year of compliance with the 2015 IWUIC where it is cost-effective to do so.

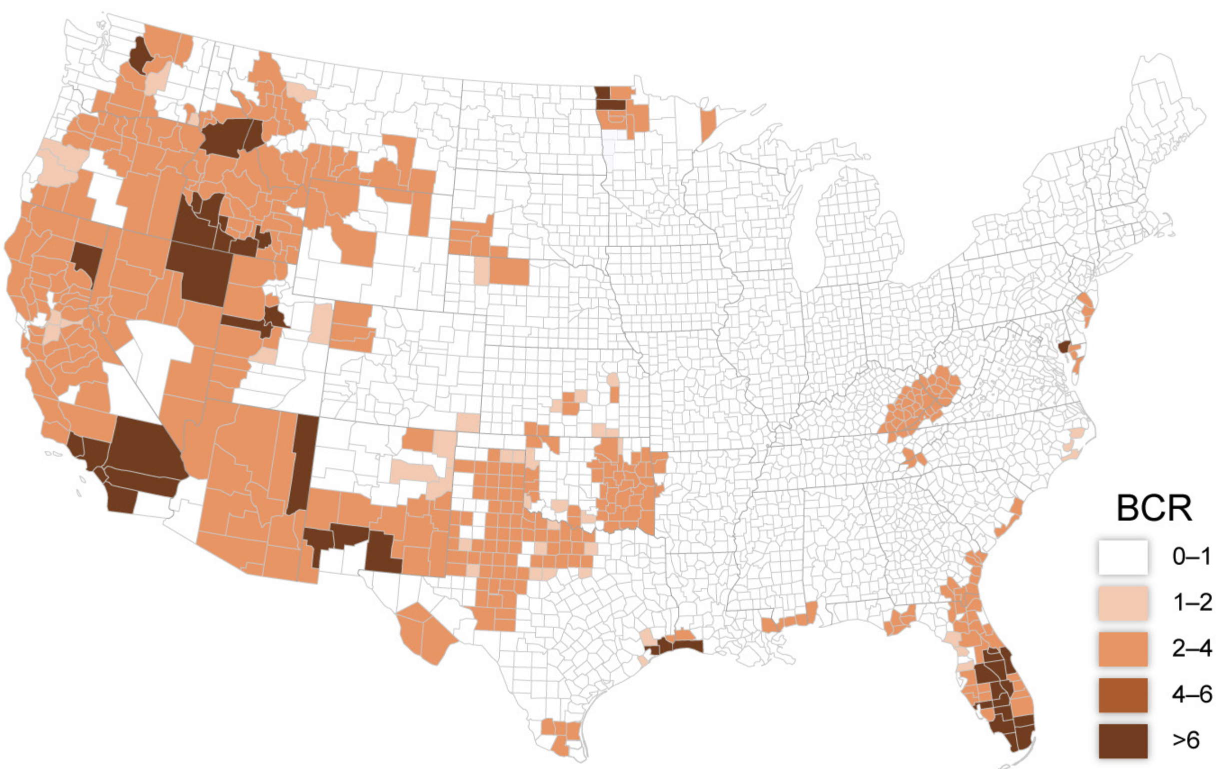

Figure 2. BCR of WUI fire mitigation by implementing the 2015 IWUIC for new buildings (by county).

National Institute of BUILDING SCIENCES

Mitigation Saves:

Mitigation Measures Reduce Injuries & Deaths, Create Jobs

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study*,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

While monetary savings received from implementing mitigation measures to exceed select 2015 code requirements and through federal grants of $4 to $1 and $6 to $1 respectively are significant, people and communities benefit from mitigation in other ways. Disasters disconnect people from friends, schools, work and familiar places. They ruin family photos and heirlooms and alter relationships. Large disasters may cause permanent harm to one's culture and way of life, and greatly impact the most socially and financially marginal people. Disasters may have long-term consequences to the health and collective well-being of those effected. These events often hurt or kill pets and destroy natural ecosystems that are integral parts of communities. The temporary and sometimes permanent shifts of populations after disaster impacts those communities receiving and adapting to an unexpected influx of people.

Injuries, Deaths and Post-Traumatic Stress Disorder Cases Avoided

The project team estimated that just implementing these two segments of mitigation would prevent 600 deaths, 1 million nonfatal injuries and 4,000 cases of post-traumatic stress disorder (PTSD) in the long term.

New design to exceed the 2015 IBC and IRC and to comply with the IWUIC is estimated to prevent approximately 32,000 nonfatal injuries, 20 deaths and 100 cases of PTSD. The past 23 years of federally funded natural hazard mitigation is estimated to prevent deaths, nonfatal injuries and PTSD worth $68 billion, equivalent to approximately 1 million nonfatal injuries, 600 deaths and 4,000 cases of PTSD.

The past 23 years of mitigation dominate the estimated savings in deaths, nonfatal injuries and PTSD, compared with 1 year of design to exceed 2015 I-Code requirements, probably because (a) past grants have focused on mitigating the most-risky existing buildings, and (b) current I-Codes do a very good job of protecting life. But both kinds of mitigation do save lives. The benefit-cost ratios (BCRs) presented here already reflect the enhanced life safety using United States government figures of the acceptable cost to avoid future statistical deaths and injuries, but it seems worthwhile to remember that the safety benefits across these mitigation strategies reflect the safety of more than 1 million people and their families who will be able to continue their lives after a natural disaster because foresighted individuals, communities and governments took action and invested money to protect them before disaster struck.

Mitigation Creates Jobs

Designing new buildings to exceed the 2015 IBC and IRC would result in 87,000 new, long-term jobs, and an approximate 1% increase in utilization of domestically produced construction material.[1] The $3.6 billion increase in construction expenses to exceed the selected code provisions for one year would add 1% to current annual construction costs. Across all perils studied (flood, wind, earthquake and wildland-urban interface fire), one can estimate that new design to exceed 2015 I-Code requirements would add approximately 87,000 jobs to the construction-material industry.

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Wildland-Urban Interface Fire	3:1	4:1

Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

[1]Higher construction costs might also cost jobs if higher costs make new homes less affordable, unless the higher cost of homes is offset by incentives.

Mitigation Saves:

Architects Can Present Results to Engage Clients

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

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Examining the past 23 years of federally funded natural hazard mitigation, the project team found that society will ultimately save $6 for every $1 spent on up-front mitigation cost. The federally funded natural hazard mitigation is estimated to prevent approximately 1 million nonfatal injuries, 600 deaths and 4,000 cases of PTSD. The team also found that if all new buildings were built to the incrementally efficient maximum (IEMax) design to exceed select requirements of the 2015 IBC and IRC and compliance with the 2015 IWUIC for one year, new construction would save approximately $4 in avoided future losses for every $1 spent on additional, up-front construction cost. Such measures are estimated to prevent approximately 32,000 nonfatal injuries, 20 deaths and 100 cases of post-traumatic stress disorder (PTSD).

Architects Can Help Clients, Advance Architectural Practice

Architects serve as trusted advisors for building owners and developers that undertake new construction or major renovations. They can ask key questions during the early phases of the project (programming/pre-design) where implementation of mitigation measures is most cost-effective. They can help clients understand the potential risks associated with a project and determine an owner's risk tolerance and ability to mitigate those risks. While results from the *Interim Report* focus on new construction, future study will provide benefit-cost ratios (BCRs) for select retrofit activities.

Table 1 provides BCRs for each natural hazard the project team examined. The costs reflect only the added costs and benefits relative to the 2015 IBC and IRC. Where communities have an older code or no code in place, additional costs and benefits will accrue. If all new buildings built the year after were also designed to exceed select I-Code requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

Strategies to exceed minimum requirements of the 2015 Codes studied here include:

- For flood resistance (to address riverine flooding and hurricane surge), build new homes higher above base flood elevation (BFE) than required by the 2015 IBC.
- For resistance to hurricane winds, build new homes to comply with the Insurance Institute for Business & Home Safety (IBHS) FORTIFIED Home Hurricane standards.
- For resistance to earthquakes, build new buildings stronger and stiffer than required by the 2015 IBC.
- For fire resistance in the wildland-urban interface, build new buildings to comply with the 2015 IWUIC.

Findings from the *Interim Report* can provide architects with evidence of the kinds and quantities of mitigation that others have undertaken, the conditions and locations under which those activities appear to be most cost-effective, and the IEMax degree of mitigation. Architects can use the BCR —particularly at a local level—to articulate the value of mitigation to their clients. The ability to look across mitigation strategies and hazards addressed will allow the cost-effective optimization of projects.

Tools like those examined in the *2017 Mitigation Saves* study, including FORTIFIED and the IWUIC, alongside selected provisions to exceed the baseline code, can inform the design process and support discussion on implementing such measures in specific projects.

Architects and allied design professionals play an important role in the development of codes, standards and other guidance developed and implemented at the national and local levels. Results from this *Interim Report* and the ongoing study can inform updates to such guidance. Given their experience and expertise, architects are in an ideal position to translate findings from this study into practical, cost-effective updates and advocate for their adoption.

All Stakeholders Benefit from Mitigation Investments

All major stakeholder groups, including developers, title holders, lenders, tenants and the community, enjoy net benefits from new design to exceed the code requirements the project team studied. All of society wins when designers and builders design and construct new buildings that meet an IEMax level of design exceeding 2015 I-Code requirements where it makes financial sense, on a societal level, to do so. The benefits to tenants and owners only accrue to those who own or occupy buildings designed to exceed 2015 I-Code requirements. However, even those who do not own or occupy those buildings enjoy a share of the community benefits. (Note: This finding reflects long-term averages to broad groups, so it only speaks to the group as a whole, on average, rather than to the experience of each individual member of the group.)

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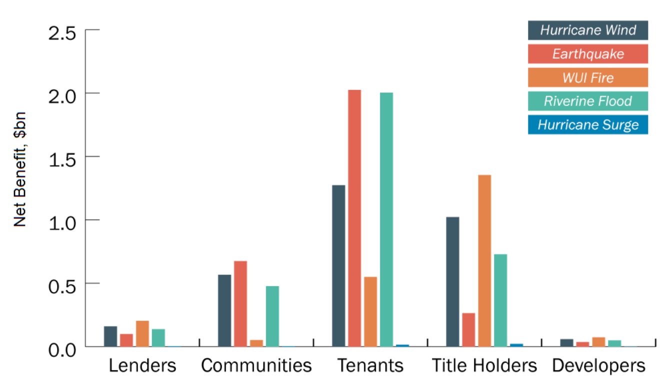

Figure 1. Stakeholder net benefits resulting from one year of constructing all new buildings to exceed select 2015 IBC and IRC requirements or to comply with 2015 IWUIC.

Mitigation Saves:

Engineers Can Present Results to Engage Clients

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study, the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
- **Beyond code requirements:** Designing new structures to exceed select provisions of the *2015 International Building Code* (IBC) and *International Residential Code* (IRC) and the adoption of the *2015 International Wildland-Urban Interface Code* (IWUIC). This resulted in a national benefit of $4 for every $1 invested.

Examining the past 23 years of federally funded natural hazard mitigation, the project team found that society will ultimately save $6 for every $1 spent on up-front mitigation cost. The federally funded natural hazard mitigation is estimated to prevent approximately 1 million nonfatal injuries, 600 deaths and 4,000 cases of PTSD. The team also found that if all new buildings were built to the incrementally efficient maximum (IEMax) design to exceed select requirements of the 2015 IBC and IRC and compliance with the 2015 IWUIC for one year, new construction would save approximately $4 in avoided future losses for every $1 spent on additional, up-front construction cost. Such measures are estimated to prevent approximately 32,000 nonfatal injuries, 20 deaths and 100 cases of post-traumatic stress disorder (PTSD).

Structural Engineers Can Help Clients, Advance Engineering Practice

Engineers provide building owners and developers that undertake new construction or major renovations and other members of the design and construction team with valuable information on opportunities to mitigate risk. They can identify such opportunities and effective solutions during the early phases of the project (programming/pre-design) where implementation of mitigation measures is most cost-effective. They can help clients understand the potential risks associated with a project and determine an owner's risk tolerance and ability to mitigate those risks. While results from the *Interim Report* focus on new construction, future study will provide benefit-cost ratios (BCRs) for select retrofit activities.

Table 1 provides BCRs for each natural hazard the project team examined. The costs reflect only the added costs and benefits relative to the 2015 IBC and IRC. Where communities have an older code or no code in place, additional costs and benefits will accrue. If all new buildings built the year after were also designed to exceed select I-Code requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

Strategies to exceed minimum requirements of the 2015 Codes studied here include:

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- For resistance to earthquakes, build new buildings stronger and stiffer than required by the 2015 IBC.
- For fire resistance in the wildland-urban interface, build new buildings to comply with the 2015 IWUIC.

Findings from the *Interim Report* can provide designers with evidence of the kinds and quantities of mitigation that others have undertaken, the conditions and locations under which those activities appear to be most cost-effective, and the IEMax degree of mitigation. Engineers can use the BCR —particularly at a local level—to articulate the value of mitigation to their clients. The ability to look across mitigation strategies and hazards addressed will allow the cost-effective optimization of projects.

Tools like those examined in the *2017 Mitigation Saves* study, including FORTIFIED, alongside selected provisions to exceed the baseline code, can inform the design process and support discussion on implementing such measures in specific projects.

Structural engineers play an important role in the development of codes, standards and other guidance developed and implemented at the national and local levels. Results from this Interim Report and the ongoing study can inform updates to such guidance. Given their experience and expertise, engineers are in an ideal position to translate findings from this study into practical, cost-effective updates and advocate for their adoption.

All Stakeholders Benefit from Mitigation Investments

All major stakeholder groups, including developers, title holders, lenders, tenants and the community, enjoy net benefits from new design to exceed the code requirements the project team studied. All of society wins when designers and builders design and construct new buildings that meet an IEMax level of design exceeding 2015 I-Code requirements where it makes financial sense, on a societal level, to do so. The benefits to tenants and owners only accrue to those who own or occupy buildings designed to exceed 2015 I-Code requirements. However, even those who do not own or occupy those buildings enjoy a share of the community benefits. (Note: This finding reflects long-term averages to broad groups, so it only speaks to the group as a whole, on average, rather than to the experience of each individual member of the group.)

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Federally Funded	Beyond Code Requirements
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Table 1. Benefit-Cost Ratio by Hazard and Mitigation Measure.

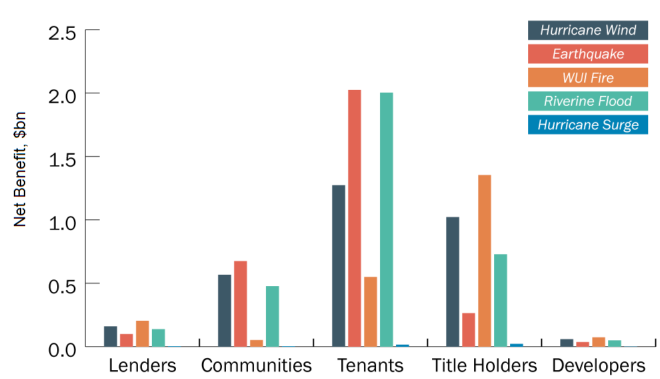

Figure 1. Stakeholder net benefits resulting from one year of constructing all new buildings to exceed select 2015 IBC and IRC requirements or to comply with 2015 IWUIC.

National Institute of BUILDING SCIENCES

Mitigation Saves:

Building Codes Set the Foundation for Mitigation Investments

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

The National Institute of Building Sciences Multihazard Mitigation Council (MMC) undertook a study in 2017 to update and expand upon the findings of its *2005 Mitigation Saves* study on the value of mitigation. In the 2017 Interim Study*,* the project team analyzed two areas of mitigation programs:

- **Federal grants:** The impacts of 23 years of federal grants made by the Federal Emergency Management Agency (FEMA), Economic Development Administration (EDA) and the Department of Housing and Urban Development (HUD), resulting in a national benefit of $6 for every $1 invested.
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If all new buildings were built to incrementally efficient maximum (IEMax) design levels to exceed select requirements of the 2015 IBC and IRC and in compliance with the 2015 IWUIC for one year, new construction would save approximately $4 in avoided future losses for every $1 spent on additional, up-front construction cost. Such measures are estimated to prevent approximately 32,000 nonfatal injuries, 20 deaths and 100 cases of post-traumatic stress disorder (PTSD). Examining the past 23 years of federally funded natural hazard mitigation, society will ultimately save $6 for every $1 spent on up-front mitigation cost. The federally funded natural hazard mitigation is estimated to prevent approximately 1 million nonfatal injuries, 600 deaths and 4,000 cases of PTSD.

Codes are the Foundation for Mitigation Investments

Building codes represent the commonly accepted requirements to protect public health, safety and the environment. They address fire, structural integrity, seismology, flood and wind protection, lighting and air quality, energy safety and efficiency, ongoing building maintenance and sanitation. Codes establish requirements for construction quality, safety, energy performance, accessibility and the well-being and comfort of their occupants. Where adopted and adequately enforced, they provide the community and individual building owners and occupants with a high-level of protection from hazard events.

As demonstrated by findings of the *Interim Report* and as will be examined within the ongoing study, there are opportunities to build on this strong foundation. Exceeding select provisions of the 2015 IBC and IRC and implementing the 2015 IWUIC can provide significant benefits. These findings can inform the code development process moving forward. However, some communities have not adopted current building codes and thus are not taking advantage of the mitigation benefits already incorporated into the codes. The benefit-cost ratio (BCR) for this scenario will be examined in the next phase of the *Mitigation Saves* study.

Table 1 provides BCRs for each natural hazard the project team examined. The costs reflect only the added costs and benefits relative to the 2015 editions of the IBC and IRC. Where communities have an older code or no code in place, additional costs and benefits will accrue. If all new buildings built the year after were also designed to exceed select I-Code requirements, the benefits would be that much greater, in proportion to the quantity of new buildings.

Strategies to exceed minimum requirements of the 2015 Codes studied here include:

- For flood resistance (to address riverine flooding and hurricane surge), build new homes higher above base flood elevation (BFE) than required by the 2015 IBC.
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- For fire resistance in the wildland-urban interface, build new buildings to comply with the 2015 IWUIC.

The BCRs and the supporting documentation provided in the *Interim Report* can help inform the ongoing code development process—both at the national and state and local levels. Mayors, city council members, state legislators and code boards can inform discussions on the adoption of updated codes and potential costs and benefits that may accrue to the community and to individual stakeholders.

The very existence of codes provides benefits that are not quantified here, but may be included in the ongoing study. Such benefits include coherence, sensibility and uniformity that leads to consistent specifications and requirements for manufacturers and suppliers, allows for the introduction of innovative systems and helps to ensure building materials perform as intended. Codes are a uniform blueprint for design professionals, builders and inspectors during the project planning and construction process.

Model code development relies on the engagement of an extensive group of diverse stakeholders working together in a consensus-based process to develop, maintain and update model codes intended for state and local implementation. The process combines science and engineering, innovations in technology and materials, economics, industry experience and consumer demand to generate some of the most comprehensive building codes in the world.

All Stakeholders Benefit from Mitigation Investments

All major stakeholder groups, including developers, title holders, lenders, tenants and the community, enjoy net benefits from new design to exceed the code requirements studied. All of society wins when designers and builders design and construct new buildings that meet an IEMax level of design exceeding 2015 I-Code requirements where it makes financial sense, on a societal level, to do so. The benefits to tenants and owners only accrue to those who own or occupy buildings designed to exceed 2015 I-Code requirements. However, even those who do not own or occupy those buildings enjoy a share of the community benefits. (Note: This finding reflects long-term averages to broad groups, so it only speaks to the group as a whole, on average, rather than to the experience of each individual member of the group.)

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Figure 1. Stakeholder net benefits resulting from one year of constructing all new buildings to exceed select 2015 IBC and IRC requirements or to comply with 2015 IWUIC.

National Institute of BUILDING SCIENCES

Mitigation Saves:

Results Can Help Educate and Train Decision Makers Responsible for Planning

Introduction

Natural hazards present significant risks to many communities across the United States. Fortunately, there are measures governments, building owners, developers, tenants and others can take to reduce the impacts of such events. These measures—commonly called mitigation—can result in significant savings in terms of safety, prevent property loss and disruption of day-to-day life.

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If all new buildings were built to optimal design to exceed select requirements of the 2015 IBC and IRC and compliance with the 2015 IWUIC for one year, new construction would save approximately $4 in avoided future losses for every $1 spent on additional, up-front construction cost. Such measures are estimated to prevent approximately 32,000 nonfatal injuries, 20 deaths and 100 cases of post-traumatic stress disorder (PTSD). Examining the past 23 years of federally funded natural hazard mitigation, society will ultimately save $6 for every $1 spent on up-front mitigation cost. The federally funded natural hazard mitigation is estimated to prevent approximately 1 million nonfatal injuries, 600 deaths and 4,000 cases of PTSD.

Education and Training of Decision Makers

Decisions made at the local level regarding development, including zoning and building codes, influence a community's susceptibility to hazard events and ultimately its resilience. Policymakers and others charged with making such decisions need education and training that provides credible information regarding the costs and benefits of various mitigation strategies. Organizations like the Natural Hazard Mitigation Association are working with FEMA and the American Bar Association (ABA) to develop disaster risk reduction curriculum.

Through the suite of mitigation measures identified, their associated benefit-cost ratios (BCRs) and the process for arriving at such BCRs, decision makers will have the tools to understand the economic arguments around various development choices and avoid poor decisions that may place undue burdens on the community.

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- For fire resistance in the wildland-urban interface, build new buildings to comply with the 2015 IWUIC.

Public-sector mitigation strategies funded through federal grants include:

- For flood resistance, acquire or demolish flood-prone buildings, especially single-family dwellings, manufactured homes and 2- to 4-family dwellings.
- For wind resistance, add shutters, safe rooms and other common measures.
- For earthquake resistance, strengthen various structural and nonstructural components.
- For fire resistance, replace roofs, manage vegetation to reduce fuels and replace wooden water tanks.

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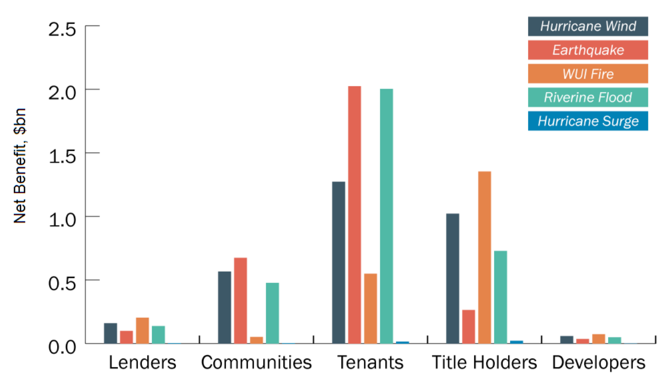

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