National Center for Risk and Economic Analysis of Terrorism Events
University of Southern California

First Responder Group (FRG)
Apex Technology Transition Impact Assessment

Draft Final Summary Report

Submitted to

First Responders Group/Office of Public Safety Research
Science and Technology Directorate
U.S. Department of Homeland Security

Attention: Jennifer Foley, Jessica Wilson

December 27, 2019

This research was supported by the United States Department of Homeland Security through the National Center for Risk and Economic Analysis of Terrorism Events (CREATE) under Basic Ordering Agreement HSHQDC-17-A-B004
However, any opinions, findings, conclusions or recommendations in this document are those of the authors and do not necessarily reflect views of the United States Department of Homeland Security or the University of Southern California.

Basic Ordering Agreement HSHQDC-17-A-B004
Department of Homeland Security

ABOUT CREATE

The National Center for Risk and Economic Analysis of Terrorism Events (CREATE) was the first university-based Center of Excellence (COE) funded by the Office of University Programs (OUP) of the Science and Technology (S&T) Directorate of the Department of Homeland Security (DHS). CREATE started operations in March of 2004 and has since been joined by additional DHS centers. Like other COEs, CREATE contributes university-based research to make the nation safer by taking a longer-term view of scientific innovations and breakthroughs and by developing the future intellectual leaders in homeland security.

CREATE's mission is to improve homeland security decisions and operations to make our nation safer. We are accomplishing our mission through an integrated program of research, education and outreach that is designed to inform and support decisions and operations faced by elected officials and governmental employees at the national, state, and local levels. We are also working with private industry, both to leverage the investments being made by the DHS in these organizations and to facilitate the transition of research toward meeting the security needs of our nation.

CREATE employs an interdisciplinary approach merging engineers, economists, decision scientists, and system modelers in a program that integrates research, education and outreach.

This approach encourages creative discovery by employing the intellectual power of the American university system to solve some of the country's most pressing problems. The Center is the lead institution where researchers from around the country come to assist in the national effort to improve homeland security through analysis and modeling of threats. The Center treats the subject of homeland security with the urgency that it deserves, with one of its key goals being to produce rapid results by leveraging existing resources so that benefits accrue to our nation as quickly as possible.

By the nature of the research in risk, economics, risk management and operations research, CREATE serves the need of many agencies at the DHS, including the Transportation Security Administration, Customs and Border Protection, Immigration and Customs Enforcement, Federal Emergency Management Agency and the US Coast Guard. In addition, CREATE has developed relationships with clients in the Offices of National Protection and Programs, Intelligence and Analysis, the Domestic Nuclear Detection Office and many State and Local government agencies. CREATE faculty and students take both the long-term view of how to reduce terrorism risk through fundamental research, and the near-term view of improving the cost-effectiveness of counter-terrorism policies and investments through applied research.

TABLE OF CONTENTS

1. INTRODUCTION

The First Responder Group (FRG) of the Science and Technology Directorate (S&T) at the Department of the Homeland Security (DHS) works with first responders across the country to ensure the technology they use while responding to an emergency keeps them better protected, better connected, and fully aware. The FRG includes three project areas:

1. First Responder Technologies
2. Flood Apex Program
3. Next Generation First Responder Apex Program

Projects supported by the First Responder Technologies Program include the development of products that improve the capabilities of law enforcement and first responders to act safely and effectively in a public safety and emergency response environment. Examples include the development of improved radio communication protocols and equipment for wildland firefighters. Projects that fall under the Flood Apex Program are aimed at improving flood protection through the enhanced mapping of flood zones, development of advanced inundation sensors, and creation of better floodproofing standards. The Next Generation First Responder Apex Program supports the development of handbooks, guidelines, demonstrations, and exercises for first responders.

The leadership of the FRG asked the Center for Risk and Economic Analysis of Terrorism Events (CREATE) to evaluate the impacts of selected projects funded by the FRG. CREATE had previously evaluated the benefits and costs of 19 projects funded by the Office of University Programs (OUP) at S&T using a novel benefit-cost analysis methodology. The intent was to apply a similar methodology to evaluate the costs and benefits of the selected FRG projects. The following projects were selected by the FRG staff for this purpose:

1. First Responder Technologies
    a. Radio Internet Protocol Communication Module
    b. Prepaid Card Reader
    c. Wildland Firefighter Advanced Personal Protection System
2. Flood Apex Program
    a. Floodproofing Standards

    b. Inundation Sensors
    c. Observed Flood Extent Mapping
3. Next Generation First Responder Apex Program
    a. First Responder Integration Handbook
    b. Integrated Demonstrations
    c. Jamming Exercises

In the first phase, CREATE researchers reviewed written materials and websites describing the nine projects and, in most cases, also interviewed program managers, principal investigators, and commercial or government users of these projects. The conclusion was that First Responder Technologies had produced tangible commercial products that could be subjected to a standard benefit-cost analysis. The projects funded under the Flood Apex program also had large potential impacts if adopted by local communities and residents. These projects could be analyzed with a benefit-cost analysis as well, with the caveat that some of the benefits depend on the adoption of the standards, sensors, and information by local communities and residents. As such, the benefits assessment involved substantial uncertainties. The three Next Generation First Responder Apex projects were one step removed from producing tangible products, instead delivering information, handbooks, and exercises. While these projects can have significant value for improving operations and decision-making, they were deemed less likely to be suitable for a benefit-cost analysis. As a result of this preliminary analysis, the CREATE team developed benefit-cost analyses for the first six projects. In addition, the team sketched impact assessment approaches for the Next Generation First Responder Apex Program.

In the following sections, we first describe CREATE's benefit-cost analysis methodology, which was previously developed under contract with OUP. Subsequently, we summarize the application of this approach to the six First Responder Technologies and Flood Apex Program projects listed above. Individual expanded papers are being developed for three of these projects, with the intent to publish them in peer-reviewed journals. In a separate section, we describe an approach to address the more indirect impacts of the Next Generation First Responder Apex Program. In the final section, we conclude with lessons learned and guidelines to improve the FRG's impact assessments and benefit-cost analyses.

2. METHODOLOGY[1]

The homeland security mission includes research and development (R&D) to improve the capabilities, operations, and decision-making of first responders. Over the past decade, the First Responder Group (FRG) of the Department of Homeland Security Science and Technology Directorate (DHS S&T) has funded numerous R&D projects to further this objective.

Over the past three years, CREATE, with funding from the DHS S&T Office of University Programs (OUP), has developed a methodology to assess the impacts of homeland security R&D projects, along with their benefits and costs. The overarching methodology is called risk-informed benefit-cost analysis, since many of the benefits of R&D projects involve the reduction of risks, and many impacts of R&D projects, like shortening response times and improving communications, are uncertain (see von Winterfeldt et al., 2019). A risk-informed benefit-cost analysis retains the probability and consequence drivers of the problem but adds valuation based on trade-offs revealed in markets or by decision-makers. Federal government guidance exists on such a benefit-cost approach (U.S. Office of Management and Budget [OMB], 1992; 2003), which was relevant to DHS managers who expressed a preference for the monetized benefit-cost value metric. Finally, although the majority of benefit-cost analyses are prospective to inform a pending decision, there are increased calls for retrospective analysis to inform analytical practice as well as continuing programmatic decisions. The cases here are retrospective to the extent possible, some blending both retrospective and prospective elements while others are entirely prospective.

In the homeland security context, risk reductions (reductions in threat, vulnerability, or consequences) and their inherent uncertainties are central drivers to the operational agencies of DHS. Concurrently, risk managers are concerned with allocating resources in ways that reduce costs or can be demonstrated to be net beneficial. Consequently, the methodological adaptations here build from changes in risk (Bedford & Cooke, 2001; Aven, 2003). Adding a management focus, we incorporate elements of decision analysis (Raiffa, 1968; von Winterfeldt & Edwards, 1986; Howard & Abbas, 2014) to obtain benefit-cost estimates in a way consistent with professional practice and government guidance (Campbell & Brown, 2015; Boardman, Greenberg, Vining, & Weimer, 2018; U.S. OMB, 1992; 2003). Risk analysis was used to

[1] This section was liberally adapted from von Winterfeldt et al., 2019.

identify and model input variables to estimate costs and benefits and to express their uncertainties through tornado analysis and probabilistic simulation. Decision analysis was used when the research products affected a specific choice (decision tree analysis), when they informed decisions (value of information analysis), or when they affected false alarms or detection rates (signal detection theory). Benefit-cost analysis was used as the guiding framework of the assessment to compare aggregated impacts with baseline performance and to express the results in monetary terms of net present value (NPV).

DHS research managers want to spend research dollars in a way that assist DHS operations and decision-making and generate an aggregate positive social return from the budget given to them. If placed in a simplified optimizing framework such as benefit-cost analysis, an expected net present value maximizer with a limited budget would expend funds on projects ranked by their expected benefit-cost ratio until the constrained budget is exhausted (Bellinger, 2018). As FRG managers desired a retrospective analysis, the sample selection of cases focused on those of high interest to the FRG and thought to generate a high positive impact. This was intentionally not a random selection of projects but a selection that follows *ex post* how the managers might have chosen to spend their budget had they more information *ex ante* about the payoffs from projects. Hence, the information to be generated is not about the average return on projects but about returns from the highest-ranked projects and the aggregate return of the *ex post* successful projects as compared with the fixed budget.

The methodology consists of the following steps:

1. Identification of research projects with high potential impact
2. Baseline performance analysis
3. Cost analysis
4. Benefits analysis
5. Analysis of net benefits, benefit-cost ratios and return on investment
6. Sensitivity and uncertainty analysis

Each of these steps are described in the following.

2.1 Selection of R&D Projects

It is not always possible to select all funded projects for impact and benefit-cost analysis. For example, in the past 15 years, FRG funded close to 100 R&D projects, and it would be impossible to analyze the impacts and benefits and costs of all of these projects. There are several possibilities to select a subset of these projects:

1. Random selection
2. Selection based on the existing commercial or governmental use
3. Selection to cover a broad range of projects funded by an agency
4. Selection based on the availability of data
5. Selection based on DHS managers' judgment of high actual or anticipated impact

In past applications, the CREATE team analyzed the benefits and costs of OUP-funded projects, primarily using the third selection method. The main reason for this was that many of the OUP-funded research projects had the potential for an application, but few had actually been used. The selection was done by asking research managers at three DHS components, the U.S. Coast Guard, the Transportation Security Agency, and Customs and Border Protection, to evaluate some 200 research projects in terms of the

1. likelihood of a successful transition to users at DHS (the original scale used ranged from 1 to 10, where 1 meant no chance of a successful transition and 10 meant the research product had been successfully transitioned and used; this scale was transformed into a 0 to 1 probability scale), and
2. judged beneficial impact, if used (on a 1 to 10 scale, 1 meaning the benefits are negligible, and 10 meaning the benefits are very high, possibly in the hundreds of millions of dollars or equivalent).

Subsequently, the 200 research products were ranked based on the product of the likelihood of transition and benefits. The process included group discussion and consensus judgments. While largely qualitative, this method was used only as a screening device to identify projects likely to generate high returns, not as the actual assessment of the potential benefits.

For the FRG project, managers selected nine R&D projects using a mix of the second, third, and fourth selection methods. Many of the FRG-funded projects had already been in use (item 2), so one concern was to represent a broad range of projects (item 3). Later, it turned out that in some cases data availability was a limiting factor, and two originally selected projects were replaced by two projects for which data was more readily available.

2.2 Baseline Performance

The baseline performance metrics varied between R&D projects and, in some cases, there were multiple metrics to be aggregated into present value. As just one example, the Wildland Firefighter Advanced Personal Protection System produced and evaluated an improved design for firefighter garments. These had two benefits: better heat absorption and resulting fire protection and improved comfort. Once these performance metrics were established, the task was to assess both the baseline ("legacy") garments and the advanced garments on these two performance criteria.

2.3 Cost Analysis

Having selected the nine FRG projects, the next step in the methodology was to assess their development and implementation costs. For this purpose, a cost-accounting template was developed that assured that all initial investments were counted, in addition to transition, implementation, maintenance, and upgrade costs to the extent possible. The cost assessment template is shown in Table 1.

Table 1. Cost-Accounting Template Used for All BCAs

COST CATEGORY	START	END	AMOUNT	SOURCE
Pre-project costs (before FRG funding)				
Project costs (FRG)				
Oversight cost at the FRG				
Transition development cost				
Implementation start up cost				
Implemementation cost (User)				
TOTAL COST				

Costs and benefits occurred in various past years, with a cut-off point of 10 past or future years of use for each project. Future values were discounted at a rate informed by professional practice and government guidance (see, for example, U.S. OMB, 1992; 2003; 2017; Moore, Boardman, & Vining, 2013; U.S. Council of Economic Advisers, 2017). The base real rate of discount chosen was 3 percent, with a range from 0 to 7 percent; where appropriate for uncertainty analysis, a triangular distribution was used.

While it is standard to apply a common discount rate across projects as above, retrospective practice is less clear, as is the particular interest rate to be used. An investigation of real interest rates between 2005 to 2016 indicated that in many of these years the real rate was close to zero (U.S. Council of Economic Advisers, 2017). The approach used throughout this project was to adjust for inflation, tying nominal past costs or benefits to purchasing power in 2017 using the Consumer Price Index (U.S. Bureau of Labor Statistics, 2017), but to use a zero-retrospective real (net of inflation) rate of interest across projects to compute the present value of historical costs and benefits as of 2017. Such a general index was used, as each individual case had slight differences in cost components, and it was thought that a general price adjustment would be the most transparent.

2.4 Benefit Analysis

Assessing the benefits of R&D projects aimed at improving homeland security decisions and operations is much more difficult than assessing their costs. The largest difficulty is that there are several types of benefits which require different assessment models. Benefit-cost textbooks are replete with models for various situations (e.g., Boardman et al., 2018), but few, if any, are specific to security. Based on previous research, we identified nine benefit models from the decision analysis literature and from benefit-cost analyses that seemed to span the case contexts (Keeney & von Winterfeldt, 2011; Center for Risk and Economic Analysis of Terrorism Events [CREATE], 2018):

1. Improved performance relative to cost
    - 1.1 Reduced cost at the same performance level
    - 1.2 Increased performance at the same cost level

2. Reduction of risks
    2.1 Reduction of threats
    2.2 Reduction of vulnerabilities
    2.3 Reduction of consequence
3. Improved signal detection capabilities
    3.1 Increased detection rates
    3.2 Reduced false alarm rates
4. Value of information for improved operations and decision-making
    4.1 Improved operations through training
    4.2 Improved decision-making through better information and communication

2.5 Net Present Value Calculations, Benefit-Cost Ratio, and Return on Investment

Cost and benefit information can be summarized in several ways: by the net benefits, the benefit-cost ratio (BCR), or the return on investment (ROI). Since costs and benefits are usually distributed over time, often with upfront costs and delayed benefits, a proper calculation has to consider the time value of money. In our methodology, as noted above, we inflate costs incurred prior to 2017 by the Consumer Price Index, and we discount future costs and benefits by the social discount rate (base case at 3 percent, sensitivity analyses at zero and 7 percent).

The BCR is defined as the ratio of the net present value (NPV) of the costs, divided by the net present value of the benefits:

$$BCR = NPV(Cost)/NPV(Benefits).$$

The ROI is the ratio (as a percentage) of the present value of the net benefits, divided by the net present value of the cost:

$$ROI = \{NPV(Benefits)-NPV(Costs)\}/NPV(Costs).$$

2.6 Sensitivity and Uncertainty Analysis

While the cost estimates are usually fairly well-established with little or no uncertainty, many of the inputs to the benefits models are highly uncertain, especially if the research product has not been implemented or used yet. For example, the decrease in detection rates of a new gun or explosives detection device remains uncertain, even after extensive testing.

CREATE's benefit-cost analysis methodology includes two sensitivity analyses and one uncertainty analysis. In the first sensitivity analysis, we calculate the break-even point at which benefits just equal the costs. For example, we determine how much the detection rate would have to be increased in order to make up the cost of a new detection device. The second sensitivity analysis uses a software package called SensIt that creates a so-called "tornado diagram" (Middleton, 2006; SensIt-153-Guide, 2017). First, we define a base case and reasonable ranges (lower and upper estimates) for each uncertain parameter of the benefits models. Then we calculate the net benefits for each parameter at its low and high levels. The tornado diagram shows the ranges of the net benefits as horizontal bars, with the largest bar at the top and successively shorter bars below (thus the name "tornado"). This diagram provides us with information about which parameters matter most to the net benefit calculations and which matter the least.

Following the tornado analysis, we conduct a complete uncertainty analysis for the parameters that matter most. Since we have to deal with multiple research products and hundreds of uncertain parameters, a complete assessment of the uncertainties using expert judgment was not feasible. Instead we used triangular distributions throughout, with the low, base case, and high estimates defining the triangular distribution for each parameter. Using these triangular distributions, we employ a probabilistic simulation software called SimVoi (Middleton, 2006; SimVoi-308-Guide, 2017) to create the distribution over the net present value for each research product. As summary measures, we use the 5^{th} percentile, the median, and the 95^{th} percentile of this distribution over net benefits.

3. SUMMARIES OF BENEFIT-COST ANALYSES OF SIX FRG PROJECTS

3.1 Prepaid Card Reader (PCR)

Analyst: Richard S. John

3.1.1 Description

The U.S. Department of Homeland Security Science and Technology Directorate (DHS S&T) partnered with the ERAD Group in 2011 to develop a tool to scan prepaid cards using existing (commercially available) hardware (VX680) for reading magnetic stripes on credit cards ("Prepaid Card Reader Fact Sheet," 2019). The investment primarily was to develop proprietary software that would automate the process of manually contacting financial institutions to determine the status of a particular prepaid card discovered at a border crossing. The software was further developed with non-DHS funding between 2015 and 2018 to link to a broader range of online data and adapted to interface with a USB Bluetooth card reader for both magnetic stripes and chips.

The PCR is currently utilized by 2,500 users in 400 physical locations and has read a cumulative total of approximately 250,000 cards in 7,400 separate investigations. The available funds average for cards read to date is approximately $250 per pre-paid card, $2,500 per debit card, and $3,500 per credit card. Initial costs for each PCR include the purchase price of approximately $1600 per unit, a one-time implementation charge of $5000, and a training charge of $1500; access to the financial database is through a subscription-based service, currently priced individually at $300 per year per license.

The primary benefit of the PCR is the recovery of funds related to money laundering from criminal activity and fraud (Curry, 2017; "DHS S&T's Prepaid Card," 2017; ERAD Group, 2019).

3.1.2 Baseline Analysis

Prior to the PCR, attempts to recover funds on prepaid cards related to fraud and money laundering were unsuccessful, largely due to the time-critical nature of freezing the funds. Once a card was discovered and an investigation began, the owner of the card would typically move the funds from the card before an investigation could be completed and a hold placed on the funds manually. Prior to the PCR, attempts to manually investigate discovered cards at the border (and other locations) were largely unsuccessful in recovering funds due to time delays in exchange of information between law enforcement and the financial institutions involved. Because few investigations resulted in recovery of funds from pre-paid cards, debit cards, and credit cards, law enforcement generally did not pursue such investigations prior to the PCR. Hence, prior to the PCR, pre-paid cards, debit cards, and credit cards were an extremely attractive means for transferring funds related to criminal activity and fraud within the U.S. or across the U.S. border.

3.1.3 Cost Analysis

We estimated the cost of the PCR project at $466,761 (in 2017 dollars), which includes the original $170,000 investment by S&T in 2011, and an additional $280,000 in non-DHS funding over a 4-year period (2015-2018). The current capability of the PCR is highly dependent on the follow-on funding since 2015.

3.1.4 Benefit Analysis

The base-case benefit analysis estimated a total benefit of $5.0 million (in 2017 dollars), accounting for the operational costs of purchasing and operating the PCRs. This analysis considers only the benefit of funds recovered on pre-paid, debit, and credit cards, and does not include any deterrence effects.

3.1.5 Net Benefits, Benefit-Cost Ratio, and Return on Investment

After subtracting the investment cost (inflated to 2017 dollars), we arrive at a base-case NPV of $4.6 million (in 2017 dollars). For the base case, the benefit-cost ratio (BCR) is 10.83, and the return on investment is 983 percent.

3.1.6 Sensitivity and Uncertainty Analysis

There is substantial uncertainty about some of the inputs to the benefit calculations. Specifically, we model the uncertainty in the average increase in funds recovered, the portion of the recovered funds that should be interpreted as a benefit, and the average annual discount rate. Using a probabilistic simulation, we estimated an expected (mean) NPV (in 2017 dollars) through 2027 of $7.5 million, ranging from $-0.2 million (5th percentile) to $6.4 million (median), to $18.9 million (95th percentile). Probabilistic simulation was also used to estimate an expected (mean) BCR of 16.64, ranging from 0.54 (5th percentile) to 14.16 (median), to 41.04 (95th percentile).

3.2 Radio Internet Protocol Communications Module (RIC-M)

Analyst: Richard S. John

3.2.1 Description

DHS S&T designed the Radio Internet Protocol Communications Module (RIC-M) as a low cost, after-market technology solution that allows agencies to upgrade and easily reconfigure legacy communications systems to be compatible with the Project 25 (P25) suite of standards (“Radio Internet-Protocol,” 2019; “RIC-M Radio IP,” 2019). Older base station equipment does not support open-standard interconnection, which hinders communication during emergencies requiring exchange of information critical for minimizing loss of life and property (Avtec Inc., 2019; “Success Story: Radio Internet-Protocol,” 2019). The RIC-M provides a Voice over Internet Protocol bridge between base stations and multi-vendor dispatch equipment, allowing all portable radios to communicate to and from dispatch consoles (“The New RIC-Mz,” 2019). In 2015, S&T obtained both the RIC-M trademark and utility patent; S&T owns the IP rights to the RIC-M technology and currently receives royalties on the sale of every RIC-M device.

3.2.2 Baseline Analysis

Prior to the RIC-M, agencies were forced to either use legacy systems with little to no interoperability, which limited communication, or to replace legacy base station equipment with newer, more expensive equipment. More recently, continued use of legacy base station equipment is becoming impossible in some contexts, requiring expensive upgrades to newer models costing up to $15,000 each. The primary benefit of the RIC-M technology is the reduced cost and ease of replacing existing systems that would have limited interoperability or would not be usable at all.

3.2.3 Cost Analysis

We estimated the cost of the RIC-M development at $312,700 (in 2017 dollars), which is the original total investment by S&T in 2012 and 2013.

3.2.4 Benefit Analysis

The base-case benefit analysis estimated a realized benefit (2015-2018) in reduced costs to agencies of $209,000 (in 2017 dollars) and a projected future benefit (2019-2027) of $4.4 million, for a total of $4.6 million dollars (in 2017 dollars). This analysis considers both reduced cost of equipment replacement to agencies, as well as the royalty collected by S&T for each RIC-M sold. Estimates of cost reduction are adjusted based on the fact that a completely new system would have even greater functionality and expected life.

3.2.5 Net Benefits, Benefit-Cost Ratio, and Return on Investment

After subtracting the investment cost (inflated to 2017 dollars), we arrive at a base-case NPV of $4.3 million (in 2017 dollars). For the base case, the benefit-cost ratio (BCR) is 14.64, and the return on investment is 1,364 percent.

3.2.6 Sensitivity and Uncertainty Analysis

There is substantial uncertainty about some of the inputs to the benefit calculations. Specifically, we model the uncertainty in the average annual number of RIC-M units purchased through 2027, the average sale price of the units, the average royalty percentage paid to S&T through 2027, the average distribution cost percentage, and the average annual discount rate. Using a probabilistic simulation, we estimated an expected (mean) NPV (in 2017 dollars) through 2027 of $6.1 million, ranging from $2.6 million (5th percentile) to $5.7 million (median), to $10.8 million (95th percentile). Probabilistic simulation was also used to estimate an expected (mean) BCR of 20.29, ranging from 9.79 (5th percentile) to 18.96 (median), to 35.54 (95th percentile).

3.3 Wildland Firefighter Advanced Personal Protection Equipment

Analysts: Stephanie Thrift and Detlof von Winterfeldt

3.3.1 Description

The Wildland Firefighter Advanced Personal Protection Equipment (WLFF PPE) project developed an advanced garment system aimed at wildland firefighters. The work was carried out and the advanced garments were tested by the U.S. Army Natick Soldier Research, Development and Engineering Center (NSRDEC) in Natick, MA, with funding from the Responder Technologies Program of the Science and Technology Directorate at DHS (U.S. Army Natick Center, 2014). The goal was to develop a garment system that had improved heat absorption qualities, was more comfortable to wear, and increased the possible work time of firefighters. In this benefit-cost analysis, we considered only the benefits of reduced injuries due to improved heat absorption of the advanced garment system. The work was conducted in close cooperation with the California Department of Forestry and Fire Protection (CAL FIRE), who provided personnel and equipment for testing the new garments in real firefighting situations.

3.3.2 Baseline Analysis

The CAL FIRE legacy garment system consisted of double-layered cotton pants, jackets, and assorted underclothing. Its predicted heat loss was estimated to be 174.3 W/m^2 (U.S. Army Natick Center, 2014, p. 6). The cost of each complete PPE system for male firefighters is approximately $998; it is slightly more for women. There are about 1,065,433 firefighters in the U.S. Estimates of the number of wildland firefighters are not precisely known. To estimate the number of wildland firefighters, we used the percentage of the number of wildland firefighter fatalities and injuries as compared to the number of fatalities of all firefighters in FEMA (2018) and NFPA (2018). The fatality percentage wildland firefighters is 9.5 percent and the injury percentage is 15.8 (see also Britton, Lynch, Torner & Peek-Asa, 2013; U.S Fire Administration, 2017). In the base case we used the lower of these two percentages, rounded to 10 percent. This resulted in an estimate of 106,543 wildland firefighters.

We assume that in the baseline these 106,543 wildland firefighters use either the legacy garment described above or similar garments. For the baseline, we can use the death and injury statistics involving the legacy garment, i.e., prior to 2014, when the new garments were introduced. Between 2007 and 2014, the average rate of firefighter fatalities related to garments was 9.25 per year (FEMA, 2018; NFPA, 2018), resulting in an individual firefighter's death rate of $8.68E^{-05}$ per year. There were also, on average, 4,890 wildland firefighter injuries related to garments in the same time period, leading to an annual injury rate of 4.59 percent.

Firefighter fatalities were values at $10 million, consistent with the academic literature on the value of a statistical life. There are many possible injuries to firefighters, ranging from mild smoke inhalation to broken bones to heat stress, heart attacks, and strokes. The range of equivalent costs of each of these injuries is different. Injuries were broken down by type in firefighter injury statistics (NFPA, 2018). In addition, we reviewed the literature on the social cost of various injuries and calculated the expected social cost of injuries to firefighters. The result, in the baseline, was about $16,000 per injury. Actual injury costs of injuries vary from $1,000 to over $1 million, and the $16,000 estimate was obtained as a weighted average the costs of all injuries.

In this analysis, we only consider fatalities and injuries. We did not consider the wearer's comfort level, which the U.S. Army Natick Center study (2014) examined with both legacy garments and the advanced systems. The advanced system scored significantly higher in judged comfort level, but it was hard to assign a dollar value to this improvement.

3.3.3 Cost Analysis

We obtained cost estimates for the legacy system by using available literature and vendor websites, which estimated the price at $987 for male garments (DHS, 2014, June; Kenyon Consumer Products, 2019; Swafford, 2017; XGO, 2019a; 2019b; Massif, 2019; CALPIA Store, 2019a; 2019b; Coaxsher, 2019a; 2019b; 2019c; 2019d; Parrish, 2019). We obtained cost estimates for the advanced system from several vendors and estimated a low-end average of $1,221 and a high end of $1,311 (DHS, 2014, June; XGO, 2019a; Bulwark Protection, 2019; Swafford, 2017; Army Navy Sales, 2019; CrewBoss, 2019a; 2019b; 2019c). As a base case, we used the midpoint between the low and high ends and estimated the cost of the advanced garment at $1,266. Thus, the main cost of the new garment is the difference between the costs of the advanced garment and the legacy garment, approximately $279. We combined this per-unit cost with a market penetration analysis in which we assumed, in the base case, a 5 percent per year market penetration for 106,543 wildland firefighters for the first five years, between 2015 and 2019 (after this, the garments purchased in 2015 would need to be replaced and the cycle begins anew). With a 5 percent market penetration per year, there will be a total of 24,107 purchases in the first five years, costing a total of $6,529,384 in 2017 dollars.

The cost to S&T was the cost of the project, which lasted from April 2011 to December 2013. We were unable to ascertain the precise costs, so we used the median cost of several projects funded by S&T during the same time period, which was about $500,000. Using inflation to adjust to 2017 dollars, we estimate the equivalent 2017 cost at $533,000. The total cost of the project, including implementation for five years, is estimated at $7,062,384.

3.3.4 Benefits Analysis

The main benefit of the advanced garment considered in this BCA is the reduction of fatalities and injuries and their associated costs. According to the U.S. Army Natick Center (2014), the new garments have an improved heat absorption coefficient of about 10 percent. As a first cut, it seems reasonable to apply this percentage to a percentage reduction in fatalities and injuries, especially as they relate to high-end injuries like heat stress, heart attacks, and strokes. Using the base line of $8.68E^{-05}$ individual annual fatality rate and 24,107 firefighters using the APPS for five years, we estimate the net present value benefits of the APPS as $10,366,666. Using the baseline 4.68 percent annual rate of injuries in combination with 24,107 firefighters using the new garments at a $16,204 per-injury cost, we arrive at a total benefit of $8,982,388 in 2017 dollars. The total benefits in 2017 dollars amount to $19,349,054.

3.3.5 Net Benefits, Benefit-Cost Ratio, and Return on Investment

Using estimates of the costs and benefits above, we determine that the net benefits (NPV of Benefits - NPV of Costs) are $12,286,670 in the base case. The benefit-cost ratio is 2.7 and the return on investment is 174 percent over 5 years.

3.3.6 Sensitivity and Uncertainty Analysis

Sensitivity analyses revealed that the input variables that influence the NPV, BCR, and ROI outputs are:

1. The probability of an injury in five years
2. The reduction of the probability of injury due to the advanced garment
3. The value of avoiding an injury (i.e. the social cost of an injury)
4. The market penetration rate

A probabilistic simulation using triangular distributions for these input variables showed a fairly large variability in net present values, ranging from a 5th percentile of $5,382,882 to a median of $11,982,629 to a 95th percentile of $40,595,460.

3.4 National Resilience Standards for Floodproofing Products

Analysts: Dan Wei, Adam Rose, and Juan Machado

3.4.1 Description

The National Resilience Standards Program for floodproofing products combines aspects of setting standards and protocols for testing and certifying floodproofing products and their adoption. Since 2012, DHS S&T has collaborated with the Association of State Floodplain Managers (ASFPM), U.S. Army Corps of Engineers (USACE), and the private product certification firm FM Approvals to expand the existing National Flood Barrier Testing and Certification Program (NFBTCP) to develop rigorous testing standards and certification protocols for new floodproofing products. The goal is to set targets for improvement of flood barriers in terms of their quality and effectiveness, in this case the ability to prevent floodwaters up to four feet in height from entering structures. The program includes products that fall into the following six broad product categories: temporary barriers, semi-permanent barriers, closure devices, backwater valves, sealants, and mitigation pumps, which are expected to provide reductions in flood losses to residential, commercial, agricultural, and industrial properties. So far, 13 products under the categories of temporary barriers and closure devices have been certified under this program (DHS, 2019). It is expected that the availability of these products and the certification of their quality and ability will induce potential users to adopt them. This pertains both to users who are already purchasing floodproofing products of lower quality/effectiveness and to those who had not previously adopted any such products.

3.4.2 Baseline Analysis

Most estimates of the adoption of dry floodproofing measures found in the existing literature are based on surveys of households and are used to explore the socio-economic and risk determinants of mitigation behavior. The adoption estimates are not easily comparable across studies as the surveys vary in terms of sampled respondents (e.g., all residents or only homeowners), the location of the households (e.g., across a wide area or only in flood-prone areas), and the way the mitigation measures are defined.

The most relevant adoption estimates are found in Botzen, Kunreuther, Czajkowski, and de Moel (2019) and Brody, Lee, and Highfield (2017), two recent works that survey households in different areas of the United States. Botzen et al. (2019) found that approximately 25 percent of New York City homeowners living in flood-prone areas owned flood shields or sand bags prior to the last major flood event (Hurricane Sandy for most homeowners) and that the adoption rate increased to 32 percent following the event. Brody et al. (2017) surveyed four different Florida and Texas coastal communities located in 100-year floodplains, 500-year floodplains, and minimal flood hazard areas. They found that 2.6 percent of the households surveyed had implemented some type of dry floodproofing techniques (including adding a waterproof veneer to exterior walls, or sealing openings with shields or sandbags). The discrepancy between the estimates presented in Botzen et al. (2019) and Brody et al. (2017) are not entirely surprising, as the latter study includes households with different risks of flooding.

3.4.3 Cost Analysis

This program was originally launched in 2012, and was developed primarily based on volunteer-led initiatives to establish initial standards, create the website, and certify products through the website. Since DHS did not actually run or finance this program, there were no direct research and development or program costs to DHS or FEMA. The program has been administered by the USACE in partnership with ASFPM and FM Approvals.

The estimated total program cost of the Floodproofing Product Standards and Certification is about $1.648 million (2017 dollars). This includes the internal coordination costs between the organizations that oversee this program and the manufacturers of the dry floodproofing products being tested and certified, the program outreach costs, the water-related and material-related test costs, and the testing equipment costs. Of these various types of costs, the water-related and material-related testing costs are paid by the manufacturers.

The product costs pertain to the price per unit of the various products developed under this program. These data have been obtained from the product vendors. For each of the certified products, the costs include both product costs and installation costs. On average, installation costs are about 30 percent to 50 percent of the product price. Moreover, we also assume that the storage costs of some of the temporary floodproofing products when not in use is near zero. It is estimated that the average dry floodproofing cost is about $6,700 per residential building and $30,000 per commercial building.

3.4.4 *Benefit Analysis*

There are three potential benefits of the program: 1) increased quality of flood protection of the certified floodproofing products; 2) increased adoption of dry floodproofing products because of the program; and 3) potentially more cost-effective (lower-cost) floodproofing products. We estimate the benefits primarily based on the assumptions of wider adoption of floodproofing products and the potential property losses that can be avoided. The effect of the relatively lower costs of these products is also taken into consideration by using the product-specific costs we obtained from the vendors.

In order to estimate the annual average property damage from flood events that can be reduced by the adoption of the certified dry floodproofing products, annual property damage costs related to floods, flash floods, debris flow, and coastal flood events from 2004 to 2018 were obtained from the National Oceanic and Atmospheric Administration's (NOAA) Storm Events Database (NOAA, 2019). Property damage estimates were also assessed from claims paid by the National Flood Insurance Program (NFIP) in the same time period for both the residential and commercial buildings (FEMA, 2019a). Over the 15-year period, the amount paid in NFIP claims on buildings and content averaged $4.2 billion per year (in 2017 dollars), of which $3.78 billion are for residential claims and $0.402 billion are for commercial claims. Over the same period, the average annual numbers of residential and commercial claims were 75,624 and 4,796, respectively. Moreover, insured losses accounted for about 46 percent of the total property damages from flood events reported by NOAA.

The following additional data and assumptions are also used in the benefit analysis:

- The adoption of the dry floodproofing products, especially the perimeter and opening barriers and protection products that have been certified by the program so far, can help reduce 25 percent of the potential property losses.
- The baseline dry floodproofing adoption rate is 8 percent in the base case.
- The program will help increase the baseline adoption rate by 20 percent (from 8 percent to 9.6 percent).

Under the base case parameters, the total annual benefits of the increased adoption of the program's certified dry floodproofing products are about $33.7 million. The ten-year discounted benefits are about $295.35 million.

3.4.5 Net Benefits, Benefit-Cost Ratio, and Return on Investment

Under the base case assumptions, the NPV of the net benefits of the program is estimated to be $272.48 million after we take into account both the program costs and the installed costs of the certified dry floodproofing products. The benefit-to-cost ratio for the implementation of the program (including the installed costs of the products) is 12.9, and the return on investment (ROI) is 1,192 percent.

3.4.6 Sensitivity and Uncertainty Analysis

The estimated net benefits associated with the National Floodproofing Products Standards and Certification Program are sensitive to some of the assumed parameters. The largest uncertainty comes from the assumptions with respect to the increased adoptions of dry floodproofing products because of the program. Other important variables include annual losses from flood events per residential building and the percentage of property losses that can be reduced by adopting dry floodproofing. The uncertainty analyses on these variables, using a Monte Carlo simulation, resulted in a mean net benefit of $447.7 million, with a 5^{th} percentile of $154.1 million and a 95^{th} percentile of $861.1 million.

3.5 Flood Inundation Sensors

Analysts: Adam Rose, Dan Wei, Juan Machado, and Kyle Spencer

3.5.1 Description

The Flood Apex project develops and tests low-cost flood inundation sensors that can readily be deployed in an internet of things (IoT) network. This can improve the prediction accuracy and lengthen the lead time of flood warning systems. DHS and the Small Business Administration have provided funding, which has progressed through three phases; the current phase evaluates commercial viability. The intent is that the availability of these products will induce potential users to adopt them. This pertains to both users who are already purchasing flood sensors of lower quality/effectiveness and those who previously had not adopted such technology but are attracted by the relatively much lower cost of the new products.

3.5.2 Baseline Analysis

Low-cost sensor systems make use of the rapid pace of technological development to deliver reliable sensing capability using low-cost hardware, which keeps the equipment, operating, and maintenance costs low. These devices are cost-effective, generally utilize solar cells or batteries and thus do not rely on electrical grids for power, and make use of existing cellular and Wi-Fi network infrastructure to transmit data, all typically already in place. More sophisticated low-cost networks may also use cloud computing or local server systems to handle data processing and network monitoring (Moreno et al., 2019). Low-cost flood sensor systems would therefore be attractive to communities that face greater-than-average flood risk but are not sufficiently covered by the high-cost federal network, or by communities that want a degree of redundancy in their flood warning systems. Additionally, rural areas facing greater-than-average risk of flooding could also be covered for a low cost, assuming adequate cellular network reception.

The National Weather Service (NWS) has a certification known as StormReady and reports that 1,452 of the 3,142 counties and county-equivalent bodies are StormReady-certified. At the same time, FEMA (2019b) reports that 98 percent of all U.S. counties or equivalents, roughly 3,080 counties, were impacted by at least one flooding event between 1996 and 2016.

3.5.3 Cost Analysis

The Flood Inundation Sensor Program consists of three phases. Phase 1, which extended from March to November 2016, provided 10 companies $100,000 each to develop specifications for flood sensors and to identify additional features that would enhance their capability. The field was then narrowed to three companies that were awarded Small Business Innovation Research (SBIR) funds to design, develop, and test the low-cost, deployable flood inundation sensors (U.S. DHS, 2018). Phase 2, which ended on August 30, 2019, involved beta-testing of sensors. A spinoff of Physical Optics Corporation, Intellisense Systems, Inc., was chosen to receive $750,000 to produce a prototype. Phase 3, which extends from July 26, 2019 to July 25, 2021, is focusing on product commercialization with the intent of being able to produce 1,000 sensors per week (Helmuth, 2019). At the outset, the federal government will pay for testing and evaluation (J. Booth, personal communication, 2019).

We assume that the private sector R&D costs are factored into the selling price of the products. The R&D costs paid by government agencies include (all converted to 2017 dollars): $1.02 million total payments to the original 10 firms, $3 million to the three semi-finalist firms, and $0.72 million to Intellisense.

Product costs pertain to the sales price of the sensor product developed under this Program, which is estimated to be about $1,500 per unit, an average of the original anticipated cost by S&T and the vendor's cost estimate, factoring in uncertainties associated with a new product. Installation costs are $10 per unit, but maintenance costs are assumed to be nil. We also assume $25 on average for ancillary costs including, for example, pre-installation, coordination, and planning. These sensors will be operated using battery and solar charging, and minimal cost. However, the cost of Internet connectivity is estimated to be $150 per sensor per year.

3.5.4 Benefit Analysis

Potential benefits from the implementation of improved warning systems pertain to protecting or relocating (contents of) property and people from flood harm and thereby reducing both property damage and deaths and injuries.

The availability of low-cost sensors reaps benefits by: improved lead time for users that already employ warning systems and increased adoption of sensors where there are none in place currently. Average current warning time is estimated to be 18 hours (in places currently with warning systems) and 6 hours (in places without any warning systems), respectively. Improvements in warning time from the adoption of low-cost sensors are assumed to be a 25 percent improvement of the 18 hours.

To determine the reduction in property damage we applied the Day curve, which calibrates the relationship between waring time and percentage reduction in property damages due to floods (Day, 1970; FEMA, 2013). The application indicates that an 18-hour warning time can reduce damages by 26 percent in the base case. This figure is a bit lower than the lower-bound in the literature of approximately 35 percent (see, e.g., Papenberger et al., 2015). We consider the estimate to be reasonable because the vast majority of the literature focuses on much larger warning systems.

As to adoption of low-cost flood sensors, we assume that 80 percent of the NWS-certified counties will adopt the new sensor and the additional adoption by non-certified counties will equal 10 percent of the number of NWS certified counties for the Base Case. We also assume an average of 3 communities or large businesses in each county adopting the new technology, which has a useful life of 5 years. Finally, we assume an average of 60 flood sensors per adoptee.

Finally, we also considered the benefits from the lower cost of Intellisense sensors compared to the other alternative IoT sensors. The cost saving is estimated to be $2,500 per sensor. The calculations differ for the two cases. Those users that already have a sensors network are considered to benefit from the entirety of the cost savings. Those users that do not currently have a sensors network, are considered to benefit from only half of the cost-savings (see von Winterfeldt et al., 2019).

3.5.5 Net Benefits, Benefit-Cost Ratios, and Return on Investment

We combine our property damage reduction assumptions and the set of assumptions for key variables affecting adoption of low-cost sensors to estimate gross benefits presented. Total benefits include life safety and reduction in property damage. Total costs include the program costs and the installed cost of sensor systems. If we consider the benefits of the increased utilization of low-cost sensors only in relation to program costs, we obtain a benefit-cost ratio (BCR) of nearly 275.3:1, with a return on investment of 27,433 percent. However, it is more appropriate to estimate the BCR in relation to the cost of implementing the sensors, which yields a BCR of 2.7 and a rate of return on investment of 174.8 percent. Note that the BCR is lower than the BCR for risk reduction tactics for floods estimated in the Mitigation Saves 1 and Mitigation Saves 2 reports (Rose et al., 2007; MMC, 2017). The main reason is that both studies included a broader range of flood hazard reduction options.

3.5.6 Sensitivity and Uncertainty Analysis

The estimated net benefits associated with the Flood Apex Low-Cost Sensors are sensitive to some of the assumed parameters, especially on the benefits side. The largest uncertainty comes from the assumptions of the number of sensors deployed by each adopting community or business. Other important variables include the discount rate and reduction in property damage from increased utilization of the sensors. The uncertainty analyses on these variables, using a Monte Carlo simulation, resulted in a median net benefit of $1.14 billion, with a 5th percentile of $0.77 billion and a 95th percentile of $1.66 billion.

3.6 Observed Flood Extent (OFE) Project

Analyst: Jonathan Eyer

3.6.1 Description

The Observed Flood Extent (OFE) project created a measure of flood vulnerability developed by MDA Information Systems under a contract with the Department of Homeland Security. The OFE program uses global satellite imagery to provide information about how frequently water was present in a given location (MDA Information Systems, 2016). The Landsat program is the longest-running satellite imagery program and has used a series of satellites to provide global images since 1973. The geographic and temporal resolution of the images has varied over time, but the resolution is relatively sharp (pixels are up to 3,600 square meters and new images are available every seven days). OFE classifies each pixel in these satellite images to identify whether water was present at the time the image was taken. By counting the number of times that water was observed since 1973, OFE provides a measure of the frequency with which water was present on given patches of land. Importantly, the Landsat images, and therefore the OFE values, are available in undeveloped areas, so historic flood events can be detected even when there was no development that would justify recording the flooding. This means that OFE could be used to alert homeowners who are not aware that they are in a flood-prone region of their risk and allow them to reduce their exposure (Botzen et al, 2019; Radiant Solutions, 2018). The initial OFE project was conducted using 11 areas of interest throughout the United States, although the project can be scaled to cover the entire country at additional cost.

3.6.2 Baseline Analysis

Without information from the OFE program, property owners will rely on the existing information that they have available about their exposure to floods. In regions that have been previously mapped for flooding studies, property owners can observe risks based on FEMA flood risk information (e.g., 100-year flood plains or 500-year flood plains) and make their decisions about mitigation behavior based on that information. The expected damage from flooding is determined by the mitigation behavior of property owners and the true risks of flooding facing the property.

3.6.3 Cost Analysis

The cost of the pilot project was approximately $260,000 (in 2017 dollars), which was paid to MDA Information Systems, a private contractor. These costs were associated with salary for staff scientists and include a 12 percent labor fee. MDA Information Systems estimates that OFE can be expanded at a cost of approximately $1 per square kilometer, meaning the entire country can be mapped for a cost of approximately $8 million (MDA Information Systems, 2016).

The benefits of OFE accrue through information-induced decisions from property owners. The costs of making these mitigation investments will fall on the property owners. While homeowners may choose to undertake dry floodproofing, like raising their homes, it is more likely that they will undertake mitigation that will undertake wet floodproofing. Wet floodproofing retrofitting costs range between $1.70 to $3.50 per square foot, meaning costs of $3,400 to $7,000 for a 2,000 square foot home (FEMA, 2017).

3.6.4 Benefit Analysis

The benefits of OFE accrue to property owners who are in areas that are identified by OFE as at risk but who are not aware of the flooding risk. Using data from Hurricane Harvey, approximately 23 percent of National Flood Insurance Program (NFIP) claims were made for properties that were not designated as an “A” flood zone by FEMA. There were approximately 4.5 million NFIP policies in force across the entire country in 2017. This would suggest that there would be around 53,000 properties in the United States that would change their behavior following additional information from the OFE program. This is based on the assumption that 17 percent of applicable homes were built in the last 20 years (based on NFIP data on construction dates in Harvey claims), and that 50 percent of eligible homeowners would respond (based on the 50 percent flood insurance uptake rate).

Based on a regression analysis of claims associated with Hurricane Harvey, homes that were designated as “X” (lower risk) had total claims approximately $10,000 less than homes that were designated “A” (higher risk), controlling for the height of the flood surge in the area. Damages from floods of other return frequencies are estimated by assuming that the $10,000 benefit is associated with a 100-year flood event (Emanuel, 2017) and using estimates from Farrow and Scott (2013) of the relative flood damages for floods of various return rates. The total benefits of OFE are calculated by adding the expected OFE benefits from each return rate.[2] The mitigation benefits are dominated by small but frequent flooding events. Because OFE is best suited towards warning property owners about infrequent events, flood reduction benefits are assumed to accrue only for events with a return frequency greater than 10 years.

Because property owners responding to new information drive the benefits of OFE, there is a discrete decision made by the property owners about whether or not to undertake additional mitigation. If the property owners observe that the expected benefits of mitigation are low relative to the costs that they face, they will not invest in mitigation and there will be no additional mitigation expenditures. This, in essence, bounds the total possible loss from the program at the amount that spent by DHS: $8 million. In the worst-case scenario, property owners will not use the information but, because the use of the information is voluntary, property owners will not incur expected losses.

Under the baseline parameters, OFE resulted in approximately $55 million (in 2017 dollars) in net benefits over a 10-year time period. While there was a total reduction in expected flood claims of $330 million, this was largely offset by increased mitigation expenditure from property owners.

3.6.5 Net Benefits, Benefit-Cost Ratio, and Return on Investment

Using the baseline parameters, we calculated the 10-year net benefits of OFE at $55 million, with a BCR of 1.2 and an ROI of 20 percent. Note that these values incorporate both the $8 million investment in the technology as well as the substantial mitigation expenditures on the part of property owners. If only the research investment is considered, the BCR is 41 and the ROI is 4,010 percent.

3.6.6 Sensitivity and Uncertainty Analysis

Across a sensitivity analysis, nearly half of scenarios resulted in property owners not increasing their mitigation expenditures, resulting in a 10-year net benefit of -$8 million (the total expenditure on OFE). The median 10-year net benefit was -$6.1 million. There is, however, substantial upside to the project. The 95th percentile 10-year net benefit was approximately $300

[2] The expected OFE benefits for each return rate are calculated by multiplying the reduction in flood claims for a flood of that return rate by the likelihood of the flood occurring in each year.

million. Because the potential losses of the program are capped at -$8 million while the benefits of the program are not capped, the average 10-year net benefit across the simulations was $57 million.

The primary driver of the uncertainty is the minimum return rate at which the OFE information is effective. The OFE benefits rely on providing information to property owners that they did not otherwise have, and it is unlikely that property owners would be unaware of frequent, annual flooding events. Because much of the expected costs from flooding are derived from small, frequent events rather catastrophic events, the benefits of OFE are sensitive to how small an event that OFE can alert property owners to (Farrow & Scott, 2013).

4. BENEFIT-COST ANALYSIS FRAMEWORK FOR INFORMATION AND TRAINING PROJECTS[3]

4.1 Next Generation First Responder Integration Handbook

The New Generation First Responders (NGFR) Apex Program has collaborated with industry and first responders to identify capability gaps in existing technology. The collaboration works toward filling these gaps by integrating current and emerging technologies to improve emergency response, responder safety, and situational awareness. To integrate these technologies, S&T's NGFR Apex program developed an architecture that uses open standards to connect on-body responder technologies with improved data analytics and alerts to make responders better protected, connected, and fully aware.

S&T's NGFR Apex program aims to encourage innovators to develop interoperable technologies that address first responder needs. To guide industry in development, design, testing, and integration of responder technologies, DHS S&T has created the *Next Generation First Responder Integration Handbook*, which outlines a "plug-and-play," standards-based environment that enables commercially developed technologies to integrate with existing first responder infrastructure. More specifically, it identifies standards, interfaces, and data flows that would allow public safety agencies to integrate hardware, software, and data of different technology solutions, building their own public safety system.

[3] Much of the material described in this section was taken from websites and other publications of the NGFR.

4.2 Integration Demonstrations

The Department of Homeland Security (DHS) Science and Technology Directorate (S&T) Next Generation First Responder program (NGFR) has held a series of integration demonstrations to test, evaluate, and showcase interoperable technologies currently in development. The tests also assessed how DHS-funded technologies, commercially developed technologies, and existing first responder systems integrate to improve response operations. Since 2016, these demonstrations have evolved from tabletop integrations to field exercises with partner public safety agencies and have grown to include more commercial technologies. Outcomes and lessons learned have produced materials to aid first responders, emergency managers, and public safety agencies to implement new technologies addressing capability gaps.

The Grant County NGFR Apex Program Technology Experiment (TechEx) was the first partnership with a rural public agency that tested the integration of physiological and location sensors, situational awareness systems, drones, datacasting, and deployable communications into a cohesive public safety solution. The Grant County DHS S&T TechEx produced the NGFR Case Study series, which explains NGFR’s efforts to provide public safety agencies guidance on deployable broadband communications, location tracking, capturing, sharing, and datacasting video, physiological monitoring, and situational awareness based on conclusions from the TechEx. The following case study series is meant to aid public safety agencies across the nation in assessing and implementing first responder technologies to assist responders in completing their mission.

4.3 Jamming Exercises

Communications provide a mission-critical lifeline for America’s first responders and federal law enforcement, ensuring they can do their jobs to protect and serve our citizens, communities, and nation. Illegal jamming of communications systems – including jamming of GPS, radio and wireless systems – poses a threat to law enforcement and public safety across the country. Jammers may interfere with public safety communications and can leave responders without vital communications and critical situational awareness. While jamming is a growing threat to public safety communications, many first responders and federal law enforcement officers across the country remain unaware that jammers exist, or that jammers can impede their communications. Federal law prohibits the operation, manufacture, sale, marketing, importation, distribution, or shipment of jamming equipment.

The U.S. Department of Homeland Security (DHS) Science and Technology Directorate (S&T) is committed to making first responders safer and more aware of jamming and its potential impact to their communications, safety and ability to execute their mission. DHS S&T works to combat jamming threats by evaluating the threat, developing and testing mitigation technologies and tactics, working with public safety agencies to update training procedures, and raising awareness of jamming threats and reporting channels. In 2016, DHS S&T held the First Responder Electronic Jamming Exercise to assess the impact of jamming on public safety communications systems and mission response and to identify gaps in training.

Building on the results of the 2016 exercise, the 2017 First Responder Electronic Jamming Exercise (JamX 17) was the next step towards making our country and communities more resilient to jamming threats. During JamX 17, DHS S&T and public safety, law enforcement, and private sector and academic partners characterized the impact of jamming on a variety of communications systems and evaluated tactics and technologies to help responders better identify, locate, and mitigate the impact of jamming. S&T's objective is to enable federal, state and local operators to recognize, respond to, report, and resolve jamming incidents without compromising the mission or endangering communities.

The First Responder Electronic Jamming Exercise Program, part of S&T's Next Generation First Responder (NGFR) Apex program, develops and adapts cutting-edge technologies to make first responders better protected, connected, and fully aware while responding to emergencies.

In July 2016, S&T assembled first responders and communications technicians from across the country to explore the effects of radio frequency interference on emergency communications. The exercise at the White Sands Missile Range in New Mexico gave participants firsthand experience dealing with intentional interference (jamming) in operational situations and spurred discussions of how to counter it through improved communications procedures.

4.4 Possible Benefit-Cost Frameworks

To conduct a benefit-cost analysis for these three projects is not easy. One would first need to establish a baseline – i.e., determine how decision-making or operations would have been conducted without the information provided or the exercises conducted. Then one would have to determine how these decisions and operations could be improved with use of the information and the exercises and, further, how these improved decisions create better outcomes in terms of reduced effort and other performance measures.

One benefit-cost framework for this type of problem is a value of information (VOI) analysis. The framework is schematically shown in Figure 1. Because we did not have sufficient information to flesh out the complete VOI benefit-cost analysis, we present only a simplified framework with notional probabilities of events.

The idea behind a VOI framework is to consider information (documents, data, etc.) that can improve decision-making. To conduct a VOI analysis, one first has to determine the expected value of making decisions without the information (the lower part of Figure 1), where a choice between two decisions, A and B, has to be made in light of uncertainty about the outcome of a possible event, which can be positive (producing high value) or negative (producing low value). The next step is to consider the same decision, but using new information (data or documents) that shed light on the likelihood of the events (the upper part of Figure 1). This information may be useful or not, which will only be revealed after the decision is made to use it – usually with some effort and cost. If useful, the information will lead to a revision of the probabilities of the events with either positive or negative outcomes. Useful information reduces the uncertainty about the events (in this case, from 0.5 for each event to 0.7 for the positive event and 0.3 for the negative event). If the information turns out not to be useful, the decision is essentially the same as if it were made without the information.

The difference in the expected value with using the information (counting the cost of collecting and using it) and without the information is called the expected value of information, which is the benefit measure of a VOI analysis.

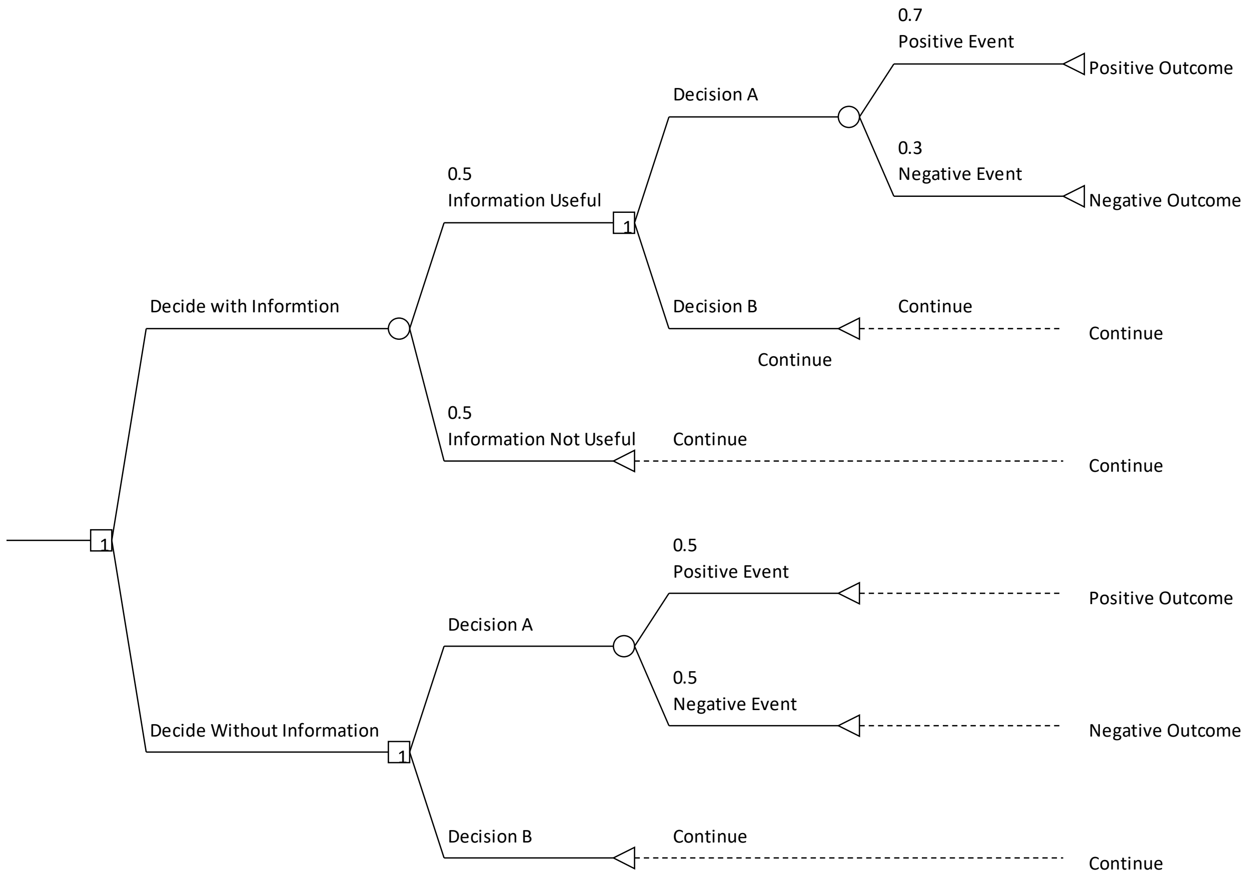

Figure 1. Value of information framework (with notional probabilities of events)

Exercises and demonstration projects or, in general, training projects, serve to improve staff performance in specific tasks. A framework for assessing what might be called the "value of training" (VOT) is shown in Figure 2.

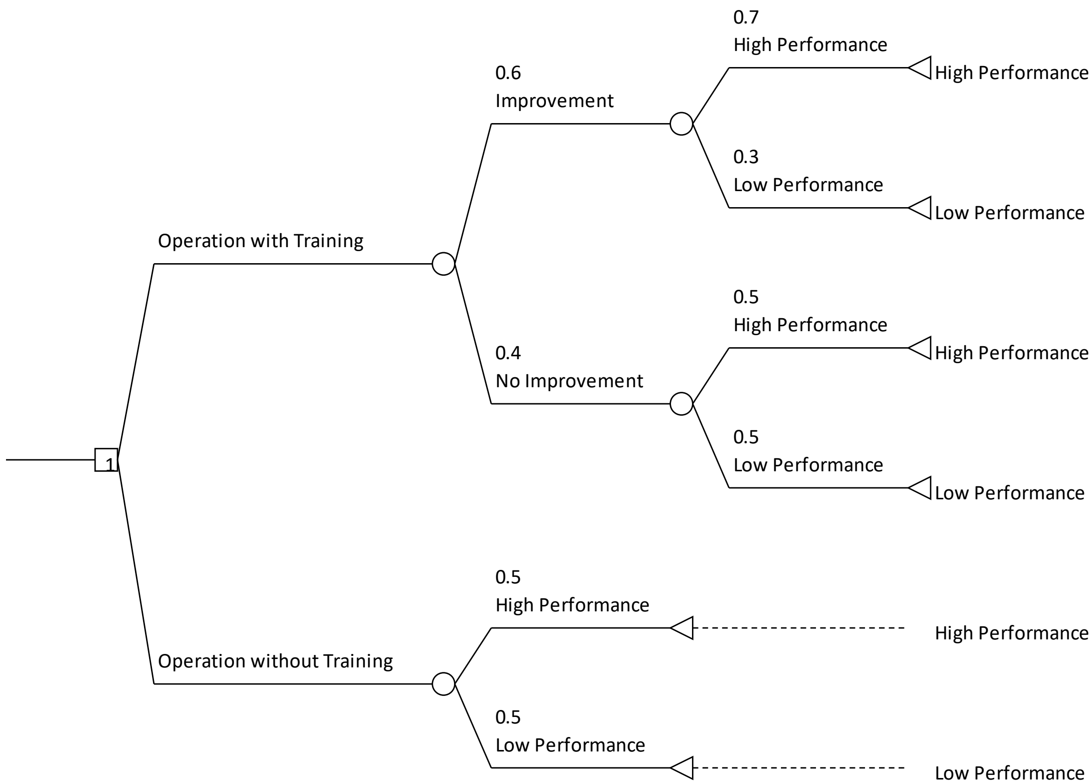

Figure 2. Value of training framework with notional probabilities

Without training, there will be some uncertainty about the actual performance in the emergency responders' operations. With training, one would expect some improvement and, thus, higher performance. The difference between the expected performance value with and without training is a measure of the benefits of training.

5. SUMMARY OF FINDINGS

Table 2 shows the base case costs, benefits, net benefits, BCR and RPI for the six projects analyzed in this study.

Table 2. Benefit Cost Analysis Results for FRG Projects
(Base Case Analysis, ordered by BCR)

Updated 11/10/19	Cost	Benefit	Net Benefit	Benefit-Cost Ratio (BCR)	Return on Investement
Radio Internet Communication Protocol	$ 312,700	$ 4,576,781	$ 4,264,081	14.6	1364%
National Resilience Standards	$ 22,866,151	$ 295,349,747	$ 272,483,596	12.9	1192%
Prepaid Card Reader	$ 466,761	$ 4,534,600	$ 4,067,839	9.7	872%
Flood Inundation Sensors	$ 675,358,046	$ 1,855,588,063	$ 1,180,230,017	2.7	175%
Wildland Firefighter Advanced Personal Protection System	$ 7,062,384	$ 19,349,054	$ 12,286,670	2.7	174%
Observed Flood Extent Project	$ 170,581,253	$ 189,008,335	$ 18,427,082	1.1	11%

For most analyses, we used the 10-year NPV of future use, calculated in 2017 dollars. There was one exception: For the Wildland Firefighter APPS project, we used the expected lifetime of the advanced garments, about five years. The net benefits vary widely across the six projects. The project on the development and implementation of flood inundation sensors has by far the largest net benefits ($1.2 billion), followed by the project on national resilience standards ($272 million). The smaller net benefits are associated with the observed flood extent project, wildland firefighter garments ($12 million), radio internet communication protocol ($4 million), and the prepaid card reader ($4 million). While the net benefits vary widely, the benefit-cost ratios are relatively modest at the lower end and comparable to recent studies on the benefits and costs of OUP-funded research projects at the higher end (see von Winterfeldt et al., 2019).

In summary, all six benefit-cost analyses showed a BCR greater than 1 and a positive ROI. This may well have been the result of selecting projects that had both available data and prior expectation of high net benefits. As stated earlier, there had been no intention to select projects randomly; the purpose was to demonstrate the use of BCA in the context of the FRG research and development projects and to demonstrate that, generally, these projects produce value.

6. LESSONS, LIMITATIONS, AND FUTURE DIRECTIONS

As in previous benefit-cost analyses of homeland security research and development products, there were lessons learned from the most general issue of model choice to detailed issues about data and parametric assumptions. At the level of model choice, we found that the benefit-cost framing of a risk value model could be used to elicit information and convey results in a way that appear useful to risk managers. At first doubtful that we could achieve monetization of the value of research products, we found that several existing models in decision analysis and benefit-cost analysis could be implemented with little or no modification. In particular, the use of sensitivity and probabilistic risk analysis allowed a degree of freedom in the analysis by taking away the need for overly precise data inputs and yet reaching sound conclusions about the net benefits, BCRs, and ROIs.

The six BCAs conducted in this study had a better basis in data and experience than some of the research projects funded by OUP in previous BCAs (von Winterfeldt et al., 2019; CREATE, 2018; 2019). The main reason for this is that most of the FRG projects had tangible products, and some were commercialized with known costs and experienced benefits. As a result, the ranges of net benefits, BCRs, and ROIs were mostly smaller than in the previous studies. Yet there remained significant uncertainties, mostly due to unknown future adoption rates, market penetration rates, and other benefits parameters. In one case (Wildland Firefighter APPS), we were unable to establish the precise FRG funding due to the departure of key program managers. Fortunately, in this case the costs were dominated by the cost of the product (firefighting garments) themselves, so that changing the up-front FRG funding expenses did not play a large role in determining NPV, BCR, and ROI.

We learned lessons that we hope can be helpful to other analysts, among them:

- Evaluating actual costs and benefits that occurred retrospectively improves the analysis as compared to a purely prospective analysis.
- Modeling changes from a baseline can sometimes bypass knowledge of absolute values of security or consequences.
- Timely documentation of baseline dimensions of risk and cost greatly facilitate any retrospective evaluation. Such estimates may come from original prospective justifications for a project.
- Quantitative uncertainty analysis in a retrospective analysis remains important, as even with hindsight few variables are known precisely.

Regarding our specific results, the benefit-cost analyses conducted during this study should be interpreted cautiously in light of the uncertainty involved in estimating benefits for some of the research products. While the cost estimates had little or no uncertainty, the benefit estimates were, in some cases, quite uncertain. The uncertainty usually stemmed from a lack of knowledge about market penetration rates, risk reduction rates, and consumer adoption rates.

The results presented in this report represent a lower bound of the net benefits of FRG R&D as they evaluate only a few of the highest-ranked projects. These benefits are rather narrowly construed, in that they do not include spinoff products or the fact that several of the projects involve basic research that would lead to still further R&D projects, as well as additional applications.

In three cases, we were unable to conduct a meaningful benefit cost analysis, because the projects resulted in documents and training exercises rather than specific useful products. For these cases, we outlined a value of information approach and a value of training approach to illustrate how benefit cost analysis, in combination with decision and risk analysis, can be carried out. Had we done these analyses, we would likely have found large uncertainties in NPVs, BCRs, and ROI (i.e., a wide range of these outputs).

We recognize that, due to these limitations, no precise benefit and cost estimates can be produced. However, one of the major benefits of conducting a combined benefit-cost and uncertainty analysis described in this paper is the identification of nine distinct benefit models that could be used by FRG and, more generally, by other DHS components as templates for future benefit-cost analyses. These models also define success metrics to identify the information that should be collected in order to reduce the uncertainty about benefits. In addition, more exact analyses could be conducted if FRG and other R&D programs would include an evaluation component to their projects in which benefits metrics are well-defined a priori and relevant data are collected in collaboration with research product users.

7. REFERENCES

Army Navy Sales. (2019). *2 Pack of GI Sand 50/50 Boxers*. Retrieved October 08, 2019, from https://www.armynavysales.com/2-pack-of-gi-sand-50-50-boxers.html

Aven, T. (2003). *Foundations of risk analysis*. New York, NY: Wiley.

Avtec Inc. (2019). *Avtec ASTRO Migration to IP with RIC-M*. Retrieved September 30, 2019, from https://www.avtecinc.com/choosing-avtec/webinars/astro-migration-to-ip-with-ric-m

Bedford, T., & Cooke, R. (2001). *Probabilistic risk analysis: Foundations and methods*. New York, NY: Cambridge University Press.

Bellinger, W. (2018). Decision Rules. In S. Farrow (Ed.), *Teaching Benefit-Cost Analysis: Tools of the Trade*. Cheltenham, UK: Edward Elgar.

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2018). *Cost-benefit analysis – Concepts and practice*. Cambridge, UK: Cambridge University Press.

Botzen, W. W., Kunreuther, H., Czajkowski, J., & de Moel, H. (2019). Adoption of Individual Flood Damage Mitigation Measures in New York City: An Extension of Protection Motivation Theory. *Risk Analysis*. DOI: 10.1111/risa.13318.

Britton, C., Lynch, C.F, Torner, J., & Peek-Asa, C. (2013). Fire characteristics associated with firefighter injury on large federal wildland fires. Annals of Epidemiology, 23, 37-41.

Brody, S. D., Lee, Y., & Highfield, W. E. (2017). Household adjustment to flood risk: a survey of coastal residents in Texas and Florida, United States. *Disasters*, *41*(3), 566-586.

Bulwark Protection. (2019). *Men's Station Wear Base Layer Tee (Athletic Style)*. Retrieved October 08, 2019, from https://www.bulwark.com/mens-station-wear-base-layer-tee-%28athletic-style%29/FT36.html

CALPIA Store. (2019a). *1st Defense-NFPA 1977:2016 Wildland Jacket*. Retrieved October 08, 2019, from https://catalog.calpia.ca.gov/product/1st-defense-nfpa-19772016-wildland-jacket-1500/

CALPIA Store. (2019b). *1st Defense-NFPA 1977:2016 Wildland Trousers*. Retrieved October 08, 2019, from https://catalog.calpia.ca.gov/product/1st-defense-nfpa-19772016-wildland-trousers-2235/

Campbell, H. F. & Brown, R. P. C. (2015). *Cost-benefit analysis*. Abingdon, UK: Routledge.

Center for Risk and Economic Analysis of Terrorism Events (CREATE). (2018). *Final Report, Center of Excellence Landscape Study – Phase I.* Los Angeles, CA: CREATE, University of Southern California.

Center for Risk and Economic Analysis of Terrorism Events (CREATE). (2019). *Center of Excellence Landscape Study – Phase 2.* Los Angeles, CA: CREATE, University of Southern California.

Coaxsher. (2019a). *CX Urban Interface Fire Coat*. Retrieved October 08, 2019, from http://www.coaxsher.com/CX-Urban-Interface-Coat-p/fc102.htm

Coaxsher. (2019b).*CX Urban Interface Vent Pants*. Retrieved October 08, 2019, from http://www.coaxsher.com/CX-Urban-Interface-Vent-Pants-p/fc202.htm

Coaxsher. (2019c). *Ethos Wildland Fire Pant*. Retrieved October 08, 2019, from http://www.coaxsher.com/Ethos-Wildland-Fire-Pant-p/fc207.htm

Coaxsher. (2019d). *Vector Wildland Fire Pant*. Retrieved October 08, 2019, from http://www.coaxsher.com/Vector-Wildland-Fire-Pant-p/fc208.htm

CrewBoss. (2019a). *Coats*. Retrieved October 08, 2019, from https://crewboss.store/collections/coats

CrewBoss (2019b). *GEN II PANTS*. Retrieved October 08, 2019, from https://crewboss.store/collections/gen-ii-pants

CrewBoss. (2019c). *INTERFACE PANT*. Retrieved October 08, 2019, from https://crewboss.store/collections/wildland-pants/products/interface-pant-6-0oz-nome

Curry, P. (2017, January/February). *Freezing assets: New technology helps law enforcement seize funds hidden on criminals' prepaid cards.* Sheriff and Deputy, p. 64. Retrieved September 30, 2019, from https://www.dhs.gov/publication/st-erad-prepaid-card-reader-article-freezing-assets

Day, H. J. (1970). *Flood Warning Benefit Evaluation-Susquehanna River Basin (urban residences)*. ESSA Technical Memorandum WBTM Hydro-10, National Weather Service, Silver Spring, MD.

DHS S&T's Prepaid Card Reader's Upgrades Make it Faster and Cheaper! (2017, May). Retrieved September 30, 2019, from https://www.newswise.com/articles/dhs-st%E2%80%99s-prepaid-card-reader%E2%80%99s-upgrades-make-it-faster-and-cheaper-

Electronic Recovery and Access to Data (ERAD) Group (2019). Retrieved September 30, 2019, from https://www.erad-group.com/

Emanuel, K. (2017). Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences*, *114*(48), 12681-12684.

Farrow, S., & Scott, M. (2013). Comparing multistate expected damages, option price and cumulative prospect measures for valuing flood protection. *Water Resources Research*, *49*(5), 2638-2648.

Federal Emergency Management Agency (FEMA). (2013). *HAZUS-MH Flood Model Technical Manual*. https://www.fema.gov/media-library-data/20130726-1820-25045-8292/hzmh2_1_fl_tm.pdf

Federal Emergency Management Agency (FEMA) (2017). *A Homeowners Guide to Retrofitting*. Available at: https://www.fema.gov/pdf/rebuild/mat/sec3.pdf

Federal Emergency Management Agency (FEMA). (2018, September). *Firefighter Fatalities in the United States in 2017*. Retrieved October 07, 2019, from https://www.usfa.fema.gov/downloads/pdf/publications/ff_fat17.pdf

Federal Emergency Management Agency (FEMA). (2019a). *FEMA NFIP Redacted Claims Data Set* [Data file]. Retrieved from https://www.fema.gov/media-library/assets/documents/180374

Federal Emergency Management Agency (FEMA). (2019b). *Data Visualization: Historical Flood Risk and Costs*. https://www.fema.gov/data-visualization-floods-data-visualization

Howard, R., & Abbas, A. (2014). *Foundations of decision analysis*. Boston, MA: Pearson.

Keeney, R.L., & von Winterfeldt, D. (2011). A value model to evaluate homeland security decisions. *Risk Analysis*, *31* (9), pp. 1470-1481.

Kenyon Consumer Products. (2019). *FR Garments*. Retrieved October 08, 2019, from https://www.kenyon.us/collections/fr-garments

Leonard, M. (2016, September). Retrieved September 30, 2019, from https://gcn.com/articles/2016/09/13/prepaid-card-reader.aspx

Massif. (2019). *Flamestretch® Sock System (FR)*. Retrieved October 08, 2019, from https://www.massif.com/shop/accessories/flamestretch-sock-system.html

MDA Information Systems. (2016). "Analysis of Historical Satellite Imagery to Map Apparent Flood Inundation Extent". BAA Number 14-02.

Middleton, M. (2006). *Decision analysis using Microsoft Excel.* Retrieved from PDFDRIVE website: https://www.pdfdrive.com/decision-analysis-using-microsoft-excel-d33613276.html

Moore, M., Boardman, A., & Vining, A. (2013). The choice of the social discount rate and the opportunity cost of public funds. *Journal of Benefit-Cost Analysis*, *4*(3), 401-409. doi:10.1515/jbca-2012-0008.

Moreno, C., Aquino, R., Ibarreche, J., Pérez, I., Castellanos, E., Álvarez, E., Clark, B. (2019). RiverCore: IoT Device for River Water Level Monitoring over Cellular Communications. Sensors, 19(1), 127.

Multihazard Mitigation Council (MMC). (2018). *Natural Hazard Mitigation Saves: 2018 Interim Report*. National Institute of Building Sciences Multihazard Mitigation Council, Washington, D.C. Retrieved from https://cdn.ymaws.com/www.nibs.org/resource/resmgr/mmc/NIBS_MSv2-2018_Interim-Repor.pdf

National Fire Protection Association (NFPA). (2018, November). *United States Firefighter Injuries 2017*. Retrieved October 07, 2019, from https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Emergency-responders/osffinjuries.pdf

National Oceanic and Atmospheric Administration (NOAA). (2019). *Storm Events Database* [Data file]. Retrieved from https://www.ncdc.noaa.gov/stormevents/

Pappenberger, F., Cloke, H. L., Parker, D. J., Wetterhall, F., Richardson, D. S., & Thielen, J. (2015). The monetary benefit of early flood warnings in Europe. *Environmental Science & Policy*, *51*, 278-291.

Parrish, J. (2019, September 18). CAL FIRE PPE Prices [E-mail to the author].

Prepaid Card Reader Fact Sheet and Video (2019). Retrieved September 30, 2019, from https://www.dhs.gov/publication/st-prepaid-card-reader-fact-sheet-and-video#

Radiant Solutions (2018). *New Urban Flood Risk*. BAA Number 14-02.

Radio Internet-Protocol Communications Module (RIC-M) Fact Sheet and Video (2019). Retrieved September 30, 2019, from https://www.dhs.gov/publication/st-ric-m

Raiffa, H. (1968). *Decision analysis.* Reading, MA: Addison-Wesley.

RIC-M Radio IP Communications Module (2019). Retrieved September 30, 2019, from https://www.acgsys.com/product/ric-m-radio-ip-communications-module/

Rose, A., Porter, K. Tierney, K., et al. (2007). Benefit-Cost Analysis of FEMA Hazard Mitigation Grants. *Natural Hazards Review*, 8, 97-111.

SensIt-153-Guide. (2017). *Sensitivity analysis using SensIt*. Retrieved from TreePlan website: https://treeplan.com/download/

SimVoi-308-Guide. (2017). *Monte Carlo simulation using SimVoi*. Retrieved from TreePlan website: https://treeplan.com/download/

Success Story: Radio Internet-Protocol Communications Module (RIC-M) (2019). Retrieved September 30, 2019, from https://www.federallabs.org/successes/success-stories/radio-internet-protocol-communications-module-ric-m

Swafford, J., Jr. (2017, August 08). *Review: New Balance introduces flame resistant sports bra and boy shorts*. Retrieved October 08, 2019, from https://www.militarytimes.com/off-duty/military-fitness/2013/08/15/review-new-balance-introduces-flame-resistant-sports-bra-and-boy-shorts/

The New RIC-Mz — Better, Faster, More Secure (2019). Retrieved September 30, 2019, from www.christinewireless.com

U.S. Army Natick Center (2014). *Advanced Personal Protection System (APPS), Wildland Firefighter Personal Protection Equipment (WLFF PPE) Clothing System.* Final Report, U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA.

U.S. Bureau of Labor Statistics. (2017). *Consumer Price Index Calculator (mid-year to mid-year).* Available at https://www.bls.gov/data/inflation_calculator.html

U.S. Council of Economic Advisers. (2017). *Discounting for Public Policy: Theory and Recent Evidence on the Merits of Updating the Discount Rate*. Issue Brief. Available at https://obamawhitehouse.archives.gov/sites/default/files/page/files/201701_cea_discounting_issue_brief.pdf

U.S. Department of Homeland Security (DHS). (2014). *Best Practices for the Treatment of a Statistical Life in U.S. Department of Homeland Security Regulatory Analyses.* D. Hauser to Component Chief Economists. Available at https://homeport.uscg.mil/Lists/Content/Attachments/540/2014%20VSL%20Memo

U.S. Department of Homeland Security (DHS). (2014, June). *Wildland Firefighter Personal Protective Equipment (PPE) Selection Guide*. Science and Technology Directorate. Retrieved October 08, 2019, from https://www.dhs.gov/sites/default/files/publications/Wild-FF-PPE-SG_0614-508.pdf

U.S. Department of Homeland Security (DHS). (2019). *National Resilience Standards for Flood Proofing Products Project*. DHS Science and Technology Directorate. Retrieved from: https://www.dhs.gov/publication/st-national-resilience-standards-flood-proofing-products-project-fact-sheet

U.S. Fire Administration. (2017). *National Fire Department Registry Summary*. Retrieved October 08, 2019, from https://www.usfa.fema.gov/downloads/pdf/registry_summary_2017.pdf

U.S. Office of Management and Budget (OMB). (1992). *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. Washington, D.C.: OMB Circular A-94.

U.S. Office of Management and Budget (OMB). (2003). *Regulatory Analysis*. Washington, D.C.: OMB Circular A-4.

U.S. Office of Management and Budget (OMB). (2017). *Appendix C: Year 2017 and History of Rates*. Accessed July 31, 2017, at https://www.whitehouse.gov/omb/circulars_a094/a94_appx-c

von Winterfeldt, D., & Edwards, W. (1986). *Decision analysis and behavioral research*. New York, NY: Cambridge University.

von Winterfeldt, D., Farrow, S., John, R, Eyer, J., Rose, A., Rosoff. H. (2019). Assessing the Benefits and Costs of Homeland Security Research: A Methodology and an Application for the U.S. Coast Guard. *Risk Analysis*, in press.

XGO, (2019a). *FR Phase 1 Advanced Cooling T-Shirt*. Retrieved October 08, 2019, from https://www.proxgo.com/collections/fr-phase-1/products/mens-fr-relaxed-fit-t-shirt-with-ac

XGO. (2019b). *FR Phase 1 Ribbed Boxer Brief*. Retrieved October 08, 2019, from https://www.proxgo.com/products/1fr13xwf-boxer-briefs?_pos=2&_sid=50a729f9d&_ss=r

APPENDIX: FULL BENEFIT-COST ANALYSES OF SIX FRG PROJECTS

Benefit-Cost Analysis of the Prepaid Card Reader (PCR)

Analyst: Richard S. John

October 2019

1. Summary

Description. The Prepaid Card Reader (PCR) is a technology that allows law enforcement to identify and suspend funds from prepaid cards that may be used in support of criminal activities. The PCR allows law enforcement to quickly scan prepaid cards and identify associated funds. The PCR allows law enforcement to differentiate prepaid cards from credit and debit cards, and to halt use of suspect prepaid cards during an ongoing investigation.

Results. The total estimated funding for the PCR was $0.467 million (in 2017 dollars), including both an initial investment from S&T and private follow-on funding. The primary benefit of the PCR is the recovery of funds related to money laundering from criminal activity and fraud (Curry, 2017; "DHS S&T's Prepaid Card Reader's Upgrades," 2017; ERAD Group, 2019). Benefit is largely dependent on the volume of cards investigated, the proportion of cards that involve fraud or concealment, and the number of PCRs in use. The base-case analysis indicates a benefit of $5.053 million (in 2017 dollars). The total net benefit is estimated to be $4.586 million (in 2017 dollars), resulting in a 983 percent ROI and a benefit-cost ratio of 10.83. A sensitivity analysis indicated a great deal of uncertainty in the net benefit, with a median of $6.394 million, ranging from $-0.163 million ($5^{th}$ percentile) to $18.906 million ($95^{th}$ percentile).

2. Description of the Project

The U.S. Department of Homeland Security (DHS) Science and Technology Directorate (S&T) partnered with the ERAD Group in 2011 to develop a tool to scan prepaid cards using existing (commercially available) hardware (VX680) for reading magnetic stripes on credit cards ("Prepaid Card Reader Fact Sheet and Video," 2019). The investment primarily was to develop proprietary software that would automate the process of manually contacting financial institutions to determine the status of a particular prepaid card discovered at a border crossing. The software was further developed with non-DHS funding between 2015 and 2018 to link to a broader range of online data and adapted to interface with a USB Bluetooth card reader for both magnetic stripes and chips.

The PCR is currently utilized by 2,500 users in 400 physical locations and has read a cumulative total of approximately 250,000 cards in 7,400 separate investigations. The available funds average for cards read to date is approximately $250 per pre-paid card, $2,500 per debit card, and $3,500 per credit card. Initial costs for each PCR include the purchase price of approximately $1,600 per unit, a one-time implementation fee of $5,000, and a training charge of $1,500; access to the financial data base is through a subscription-based service, currently priced at $300 per year per license.

The primary benefit of the PCR is the recovery of funds related to money laundering from criminal activity and fraud (Curry, 2017; "DHS S&T's Prepaid Card," 2017; ERAD Group, 2019).

3. Baseline Analysis

Prior to the PCR, attempts to recover funds on prepaid cards related to fraud and money laundering were unsuccessful, largely due to the time-critical nature of freezing the funds. Once a card was discovered and an investigation began, the owner of the card would typically move the funds from the card before an investigation could be completed and a hold placed on the funds manually. Prior to the PCR, attempts to manually investigate discovered cards at the border (and other locations) were largely unsuccessful in recovering funds due to time delays in exchange of information between law enforcement and the financial institutions involved. Because few investigations resulted in recovery of funds from pre-paid cards, debit cards, and credit cards, law enforcement generally did not pursue such investigations prior to the PCR. Hence, prior to the PCR, pre-paid cards, debit cards, and credit cards were an extremely attractive means for transferring funds related to criminal activity and fraud within the U.S. or across the U.S. border.

4. Cost Analysis

PCR cost estimates were provided by Steve Beckerman, ERAD Chief Operating Officer. Table 1 provides a summary of the PCR development cost, including an initial investment of $0.17 million by S&T in 2011 and private funding totaling $0.28 million between 2015 and 2018. The private investment portion was distributed evenly over the four-year period. The current capability of the PCR is highly dependent on the follow-on funding since 2015. The total cost to develop the PCR totals $0.467 million (in 2017 dollars).

Table 1. PCR Cost Estimate

COST CATEGORY	START	END	AMOUNT	SOURCE
Pre-project costs (before FRG funding)				
Project costs (FRG)	Jan., 2011	Dec., 2011	$ 170,000	$ 185,300
Oversight cost at the FRG				
Transition development cost	Jan., 2015	Dec., 2018	$ 280,000	$ 281,461
Implementation start-up cost				
Implementation cost (User)				
TOTAL COST			$ 450,000	$ 466,761

5. Benefit Analysis

The base case benefit analysis estimated a benefit in recovered funds (2015-2027) of $5.053 million (in 2017 dollars). This analysis considers only the benefit of funds recovered on prepaid, credit, and debit cards and does not include any deterrence effects. The analysis also accounts for PCR operational costs, including initial purchase, training, and annual cloud service fees. Prior to the PCR, successful recovery of funds was unlikely; hence, investigation was rarely pursued. Thus, estimated costs of law enforcement staffing required for investigating prepaid, credit, and debit cards was included as an operational cost of the PCR

Base case values for 15 parameters used to calculate benefits are provided in Table 2. The first five parameters all relate to costs of acquiring and operating each PCR. The next two parameters account for increases (and decreases) in PCRs in operation over time. Parameter values for the discount rate and the benefit reduction parameter are consistent with other analyses in this report. The next seven parameters relate to the funds recovered from prepaid, credit, and debit cards investigated, and the final parameter relates to time required by law enforcement to investigate prepaid, credit, and debit cards.

As summarized in Table 2, the projected benefit accrued from funds recovery for the entire period through 2027 is estimated to be $5.053 million (in 2017 dollars).

Table 2. PCR Base Case Benefit Analysis and Benefit-Cost Summary

Variable	Base Case
Average Cost Per Unit	$ 1,600
Average Cloud Service Annual License	$ 300
Average New Unit Implementation Fee	$ 5,000
Average New Unit Training Cost	$ 1,500
Average Annual Cost of LEO User (fully loaded)	$ 150,000
Average # New units sold per year	100
Average % Units retired per year	10.00%
Average Discount Rate 2018-2027	3.00%
Average Benefit Adjustment	50%
Average recovered per pre-paid card	$ 250
Average recovered per credit or debit card	$ 3,000
Average cards read per year per PCR	200
Average % of concealment or fraud	1.00%
Average % pre-paid card of total read	33.00%
Average time to read and rec 1 card (min)	1.00
	Calculated
Total Benefits 2010-2027 (2017 $)	***$ 5,052,729***
Net Benefits (2017 Dollars)	***$ 4,585,968***
Return on Investment (ROI)	**983%**
Benefit to Cost Ratio	**10.83**

6. Net Benefits, Benefit-Cost Ratio, and Return on Investment

The PCR base case benefit-cost analysis is summarized at the bottom of Table 2. The PCR base case net benefit is estimated to be $4.586 million (in 2017 dollars). The PCR is estimated to have an ROI of 983 percent through 2027 and a benefit cost ratio of 10.83.

7. Sensitivity and Uncertainty Analysis

Break-even analysis. A break-even analysis indicates that the entire development cost of the PCR would be recovered by the end of 2019, assuming the base case parameters and assumptions described in section 5.

Tornado and sensitivity analysis. A sensitivity analysis was conducted for the net benefit, varying the 15 input parameters to the model. Table 3 summarizes the ranges for each of the three input variables for the benefit calculation; the base case values are also included for reference. Note that the "High" output column represents the value that produces the greatest net benefit, and the "Low" output column represents the value that produces the lowest net benefit. Net benefit is greater for lower benefit adjustment (parameter closer to 100 percent), greater annual increase in prepaid cards recovery, and a lower future discount rate. The ranges selected are intentionally broad and are expected to span nearly all feasible values for these parameters.

Table 3. Ranges for 15 Parameters in PCR Net Benefit Calculation Sensitivity Analysis

Variable	Low	Base	High
Average Cost Per Unit	$ 2,000	$ 1,600	$ 1,200
Average Cloud Service Annual License	$ 400	$ 300	$ 200
Average New Unit Implementation Fee	$ 6,000	$ 5,000	$ 4,000
Average New Unit Training Cost	$ 1,800	$ 1,500	$ 1,200
Average Annual Cost of LEO User (fully loaded)	$ 165,000	$ 150,000	$ 135,000
Average # New units sold per year	50	100	200
Average % Units retired per year	15.00%	10.00%	5.00%
Average Discount Rate 2018-2027	7.00%	3.00%	0.00%
Average Benefit Adjustment	25.0%	50.0%	75.0%
Average recovered per pre-paid card	$ 100	$ 250	$ 400
Average recovered per credit or debit card	$ 2,000	$ 3,000	$ 4,000
Average cards read per year per PCR	50	200	400
Average % of concealment or fraud	0.50%	1.00%	2.00%
Average % pre-paid card of total read	25.00%	33.00%	40.00%
Average time to read and rec 1 card (min)	2.00	1.00	0.50

Results of the sensitivity analysis are presented in Figure 1 as a tornado diagram. The vertical line represents the base case net benefit ($4.586 million) when all 15 variables are fixed at their base case values (see Table 3). The horizontal bars represent the range of PCR net benefits when the variable indicated on the left varies from the low to high values specified. The variables are arranged from top to bottom in relation to their impact on PCR net benefit.

Net benefits are largely determined by the volume of cards read per PCR and the percentage of cards investigated resulting in recovery of funds. In addition, net benefits are also sensitive to the rate in which PCRs are implemented, as well as the average amount recovered from fraudulent credit and debit cards. Note that net benefits are not very sensitive to parameters related to the costs of acquiring and operating the PCR. Net benefits range considerably, from -$3.3 million (50 cards read per PCR), to over $18 million, depending on the number of cards read and the percentage of cards scanned that result in recovery. The negative values for net benefit (resulting from reduced card scanning and lower proportion of recovery from cards scanned) capture a scenario in which the PCR serves as a deterrent. The current analysis does not attempt to quantify the deterrence value of the PCR.

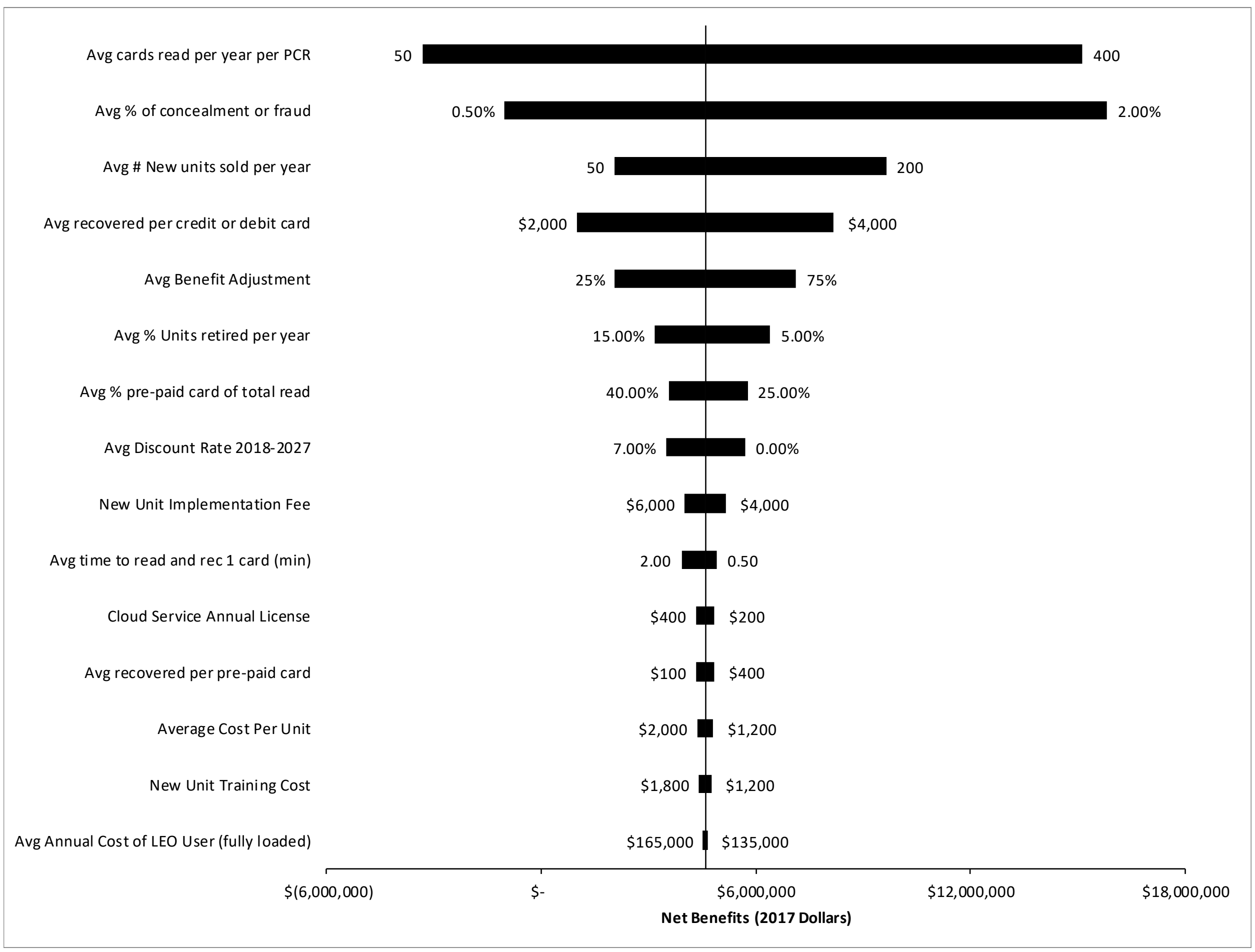

Figure 1. Tornado diagram results of sensitivity analysis

Uncertainty analysis. A Monte Carlo simulation was used to estimate a probability distribution over the net benefit of the PCR. For all 15 input variables to the benefit calculation, a triangular distribution was constructed using the base case estimate as the mode, and the low and high values defined in Table 3. All input probability distributions are constructed to be independent and thus uncorrelated. A total of 10,000 trials were sampled using Latin hypercube sampling, which is more efficient than random sampling.

Summary statistics for the PCR uncertainty analysis are presented in Table 4. The PCR mean net benefit ($7.452 million) is somewhat greater than the median ($6.394 million), indicating a right-skewed distribution. The PCR net benefit interquartile range (IQR) is approximately $7.5 million ($3.058 million to $20.526 million). The PCR net benefit 90 percent-credible interval is just over $19 million (-$0.163 million to $18.906 million).

Table 4. Summary Statistics for PCR Net Benefit Uncertainty Analysis

Mean	$	7,451,750
St. Dev.	$	6,002,272
5th %-tile	$	(163,295)
First Quartile	$	3,058,302
Median	$	6,393,888
Third Quartile	$	10,526,295
95th %-tile	$	18,905,766

A histogram of the PCR net benefit (in 2017 dollars) based on N=10,000 trials is presented in Figure 2. The distribution is single-peaked and right-skewed. The corresponding cumulative distribution of the PCR net benefit (in 2017 dollars) is presented in Figure 3. The cumulative distribution graphically displays all percentiles as cumulative probabilities, including those summarized in Table 4. Both Figures 2 and 3 convey graphically the substantial PCR net benefit uncertainty. As discussed above, much of this uncertainty is due to unpredictability in the volume of concealment and fraud over time, which depends greatly on the deterrence value of the PCR.

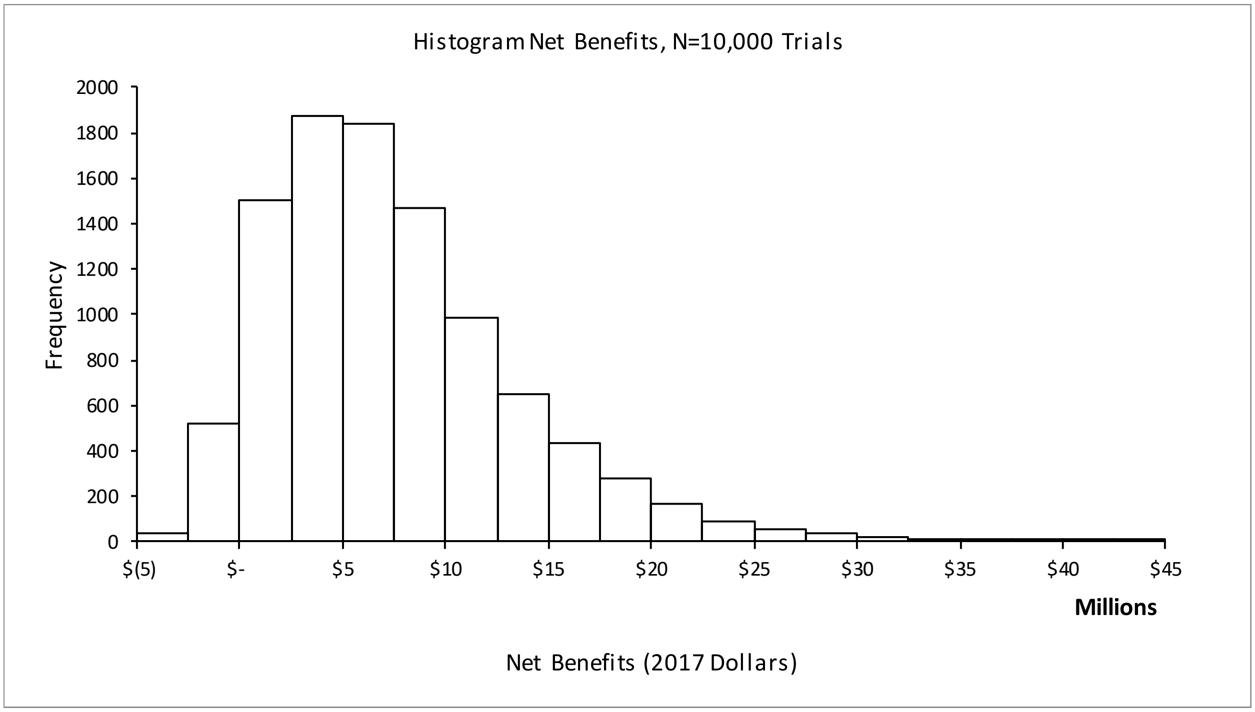

Figure 2. Histogram of PCR net benefits (N=10,000 trials)

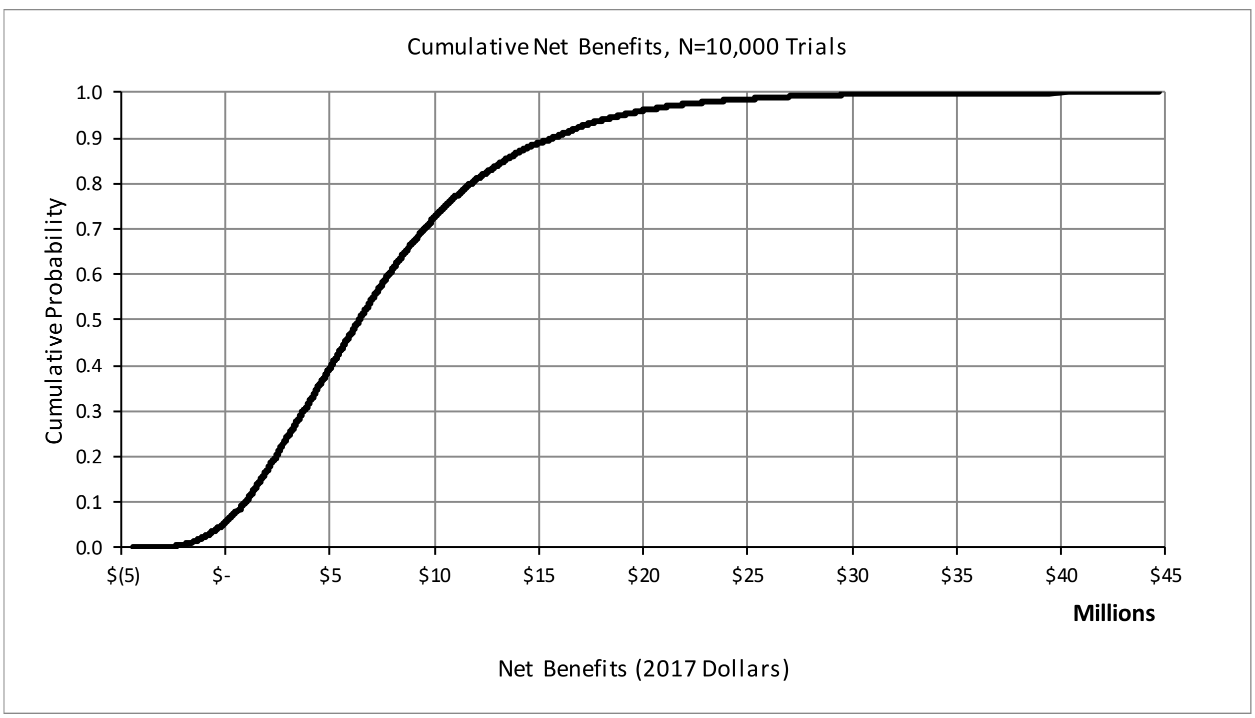

Figure 3. Cumulative distribution of PCR net benefits

8. Assumptions and Limitations

This analysis depends on a number of assumptions. First, the PCR benefit is conceptualized as the funds recovered from investigations of prepaid, credit, and debit cards related to criminal activity, minus acquisition and operational costs. The base case analysis assumes there is no deterrence effect due to law enforcement's use of PCRs. Ranges for all 15 model parameters are speculative and are used to provide both sensitivity and uncertainty analyses spanning a range of plausible values, including those associated with deterrence effects.

9. Additional Research

The most useful information to sharpen this analysis is a more informed estimate of the number of future PCRs installed and the dollar value of recovered funds on prepaid, credit, and debit cards. Tracking these data over time would allow for a better estimate of the potential deterrent effect of the PCR. As the tornado diagram indicates, PCR net benefit depends heavily on the volume of cards investigated and the percentage of cards for which funds are recovered, both of which are sensitive to deterrence effects of PCR usage.

10. References

Curry, P. (2017, January/February). Freezing assets: New technology helps law enforcement seize funds hidden on criminals' prepaid cards. Sheriff and Deputy, p. 64. Retrieved September 30, 2019, from https://www.dhs.gov/publication/st-erad-prepaid-card-reader-article-freezing-assets

DHS S&T's Prepaid Card Reader's Upgrades Make It Faster and Cheaper! (2017, May). Retrieved September 30, 2019, from https://www.newswise.com/articles/dhs-st%E2%80%99s-prepaid-card-reader%E2%80%99s-upgrades-make-it-faster-and-cheaper-

Electronic Recovery and Access to Data (ERAD) Group (2019). Retrieved September 30, 2019, from https://www.erad-group.com/

Leonard, M. (2016, September). Retrieved September 30, 2019, from https://gcn.com/articles/2016/09/13/prepaid-card-reader.aspx

Prepaid Card Reader Fact Sheet and Video (2019.). Retrieved September 30, 2019, from https://www.dhs.gov/publication/st-prepaid-card-reader-fact-sheet-and-video#

Benefit-Cost Analysis of the Radio Internet-Protocol Communications Module (RIC-M)

Analyst: Richard S. John

October 2019

1. Summary

Description. The Radio Internet-Protocol Communications Module (RIC-M) is an after-market P25-compatible technology solution that allows first responders to communicate across jurisdictions during joint operations or crises. The P25 suite of standards ensures that equipment can reliably communicate regardless of manufacturer and allows interoperability among different systems. The RIC-M allows agencies to upgrade legacy systems at a substantially lower cost than replacement, delaying replacement for another 10 to 20 years.

Results. The total estimated funding for the RIC-M was $0.313 million (in 2017 dollars). The primary benefits of the RIC-M are the cost savings of extending the life of legacy base station equipment and a 7 percent royalty that is paid to DHS S&T on each unit sold. The benefit is largely dependent on the number of projected RIC-M deployments through 2027. The base case analysis indicates a total benefit of $4.577 million (in 2017 dollars). The total net benefit is estimated to be $4.264 million (in 2017 dollars), resulting in a 1,464 percent ROI and a benefit-cost ratio of 13.64. A sensitivity analysis indicated a great deal of uncertainty in net benefits, with a median of $5.666 million, ranging from $2.710 million (5th percentile) to $10.758 million (95th percentile).

2. Description of the Project

The U.S. Department of Homeland Security (DHS) Science and Technology Directorate (S&T) designed the Radio Internet Protocol Communications Module (RIC-M) as a low-cost, after-market technology solution that allows agencies to upgrade and easily reconfigure legacy communications systems to be compatible with the Project 25 (P25) suite of standards (“Radio Internet-Protocol,” 2019; “RIC-M Radio IP,” 2019). Older base station equipment does not support open-standard interconnection, which hinders communication during emergencies requiring an exchange of information critical for minimizing loss of life and property (Avtec Inc., 2019; **“**Success Story**:** Radio Internet-Protocol,” 2019). The RIC-M provides a Voice over

Internet Protocol (VoIP) bridge between base stations and multi-vendor dispatch equipment, allowing all portable radios to communicate to and from dispatch consoles ("The New RIC-Mz," 2019). In 2015, S&T obtained both the RIC-M trademark and utility patent; S&T owns the IP rights to the RIC-M technology and currently receives royalties on the sale of every RIC-M device.

3. Baseline Analysis

Prior to the RIC-M, agencies were forced to either use legacy systems with little to no interoperability, which limited communication, or to replace legacy base station equipment with newer, more expensive equipment. More recently, continued use of legacy base station equipment is becoming impossible in some contexts, requiring expensive upgrades to newer models costing up to $15,000 each. The primary benefit of the RIC-M technology is the reduced cost and ease of replacing existing systems that would have limited interoperability or would not be usable at all.

4. Cost Analysis

RIC-M cost estimates were provided by Richard Brockway. Table 1 provides a summary of the RIC-M development cost of $0.313 million (in 2017 dollars) provided by S&T in 2012-2013. This investment was distributed evenly over the two-year period for purposes of accounting for inflation.

Table 1. RIC-M Cost Estimate

COST CATEGORY	START	END	AMOUNT	SOURCE
Pre-project costs (before FRG funding)				
Project costs (FRG)	Jan., 2012	Dec., 2013	$ 295,000	$ 312,700
Oversight cost at the FRG				
Transition development cost				
Implementation start-up cost				
Implementation cost (User)				
TOTAL COST			$ 295,000	$ 312,700

5. Benefit Analysis

The base case benefit analysis utilizes historical sales records from 2015 through mid-2019. Benefits are estimated to be equal to the cost of the RIC-M, which considers both the substantial savings of not purchasing a new replacement system, as well as the decrement in both performance and expected system life. This analysis considers both reduced cost of equipment replacement to agencies, as well as the royalty collected by S&T for each RIC-M sold. Estimates of cost reduction are adjusted, given that a completely new system would have even greater functionality and expected life. The base case benefit analysis estimated a total benefit of $4.576 million (in 2017 dollars).

As indicated in section 3, the benefit of the RIC-M includes both prior and future cost savings and a royalty paid to DHS S&T for each device sold, after distribution costs. Future sales of the RIC-M are based on projected sales approximately equal to annualized sales from the first half of 2019, constant costs for distribution, and no change in the current royalty agreement. Base case values for six parameters (royalty to S&T; distribution cost as a percentage of sales price; cost savings discounted for functionality and life-span as a percentage of sales price; future discount rate; benefit adjustment accounting for excess units sold that would not have been replaced; and the average number of units sold annually) used to calculate benefits are provided in Table 2. All base case values are based on prior sales and cost data. A 3 percent average annual discount rate is also assumed. A value of 50 percent is used as the base case estimate of excess units sold that would not have been replaced if not for the availability of the RIC-M. A base case of 100 percent cost savings is used to discount the difference between base station replacement cost and the RIC-M purchase price to account for reduced functionality and lifespan. As summarized in Table 2, the total benefit for the entire period through 2027 is estimated to be $4.576 million (in 2017 dollars).

Table 2. RIC-M Base-Case Benefit Analysis and Benefit-Cost Summary

Variable	Base Case
S&T Royalty	7%
Distributor	30%
New Comm Equip Increased Cost	100%
Average Discount Rate 2018-2027	3.00%
Benefit Adjustment	50%
Average Annual # of units sold	900
	Calculated
Past Benefits 2015-2017 (2017 $)	*$ 209,001*
Future Benefits 2018-2027 (2017 $)	*$ 4,367,780*
Total Benefits 2015-2027 (2017 $)	*$ 4,576,781*
Net Benefits (2017 Dollars)	*$ 4,264,081*
Return on Investment (ROI)	*1364%*
Benefiit to Cost Ratio	*14.64*

6. Net Benefits, Benefit-Cost Ratio, and Return on Investment

The RIC-M base case benefit-cost analysis is summarized at the bottom of Table 2, considering benefits of units sold since 2015 and projected sales through 2027. The base case net benefit is estimated to be $4.264 million (in 2017 dollars). The RIC-M is estimated to have an ROI of 1,364 percent through 2027 and a benefit-cost ratio of 14.64.

7. Sensitivity and Uncertainty Analysis

Break-even analysis. A break-even analysis indicates that the entire development cost of the RIC-M would be recovered by the end of the third year of sales (2015-2017), assuming the base case parameters and assumptions described in section 5.

Tornado and sensitivity analysis. A sensitivity analysis was conducted for net benefits, varying all eight input parameters to the model. Table 3 summarizes the ranges for each of the six input variables for the benefit calculation; the base case values are also included for reference. Note that the "High" output column represents the value that produces the greatest net benefit, and the "Low" output column represents the value that produces the lowest net benefit.

Net benefit is greater for higher S&T royalties, higher distribution costs, higher cost savings, a higher benefit adjustment parameter (closer to 100 percent), greater future RIC-M annual sales, and a lower future discount rate. The ranges selected are intentionally broad and are expected to span nearly all feasible values for these parameters.

Table 3. Ranges for Six Parameters in RIC-M Net Benefit Calculation Sensitivity Analysis

Variable	Low	Base	High
S&T Royalty	5.00%	7.00%	10.00%
Distributor	20%	30%	40%
New Comm Equip Increased Cost	50%	100%	200%
Average Discount Rate 2018-2027	7.00%	3.00%	0.00%
Benefit Adjustment	25%	50%	100%
Average Annual # of units sold	600	900	1200

Results of the RIC-M sensitivity analysis are presented in Figure 1 as a tornado diagram. The vertical line represents the base case net benefit ($4.264 million) when all six variables are fixed at their base case values (see Table 3). The horizontal bars represent the range of RIC-M net benefits when the variable indicated on the left varies from the low to high values specified. The variables are arranged from top to bottom in relation to their impact on RIC-M net benefits. By far, the greatest impact is from the benefit adjustment factor. Net benefits range from $1.976 million (if only 25 percent of benefits are related to equipment replacements that would have occurred without the RIC-M), to $8.841 million (if 100 percent of replacements would be required without availability of the RIC-M). Net benefit swings are considerable, ranging from a high of $6.865 million (benefit adjustment parameter) to a low of $0.061 million (distribution costs).

This analysis demonstrates that even the most pessimistic assumption for any one of the three input variables still results in a net benefit greater than $1.97 million. Likewise, this analysis demonstrates that the estimated RIC-M net benefit is approximately double that estimated in the base case, given more optimistic estimates of the percentage of purchases that would have been made were the RIC-M not available and estimates of the cost savings per unit.

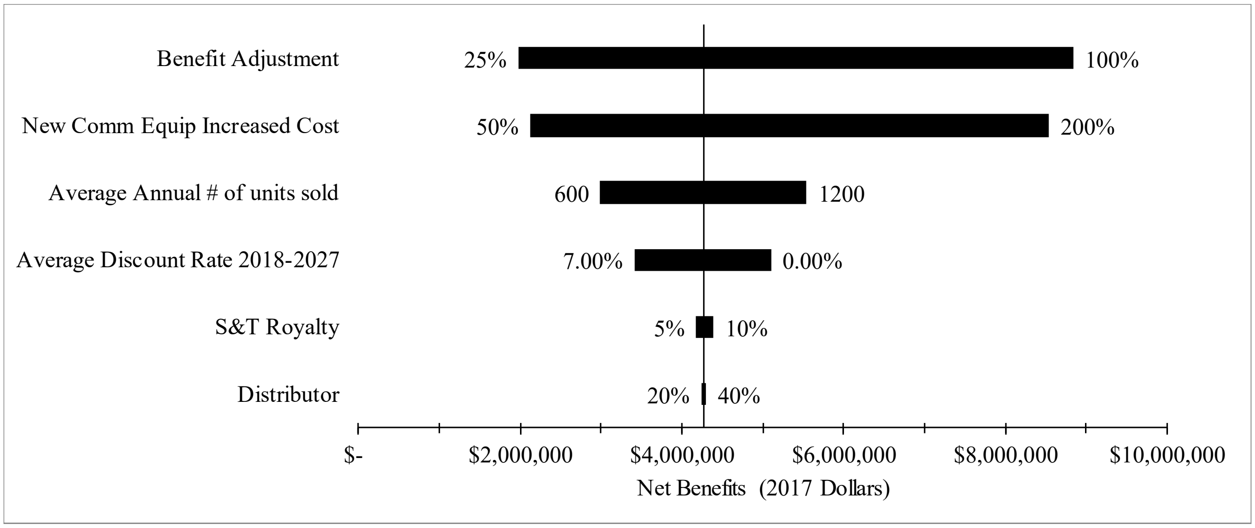

Figure 1. Tornado diagram results of sensitivity analysis

There is substantial uncertainty about some of the inputs to the benefit calculations. Specifically, we model the uncertainty in the average annual number of RIC-M units purchased through 2027, the average sale price of the units, the average royalty percentage paid to S&T through 2027, the average distribution cost percentage, and the average annual discount rate. Using a probabilistic simulation, we estimated an expected (mean) NPV (in 2017 dollars) through 2027 of $6.1 million, ranging from $2.6 million (5th percentile) to $5.7 million (median) to $10.8 million (95th percentile). Probabilistic simulation was also used to estimate an expected (mean) BCR of 20.29, ranging from 9.79 (5th percentile) to 18.96 (median) to 35.54 (95th percentile).

Uncertainty analysis. A Monte Carlo simulation was used to estimate a probability distribution over the net benefit of the RIC-M. For all six input variables to the benefit calculation, a triangular distribution was constructed using the base case estimate as the mode and the low and high values defined in Table 3. Note that four of the six distributions are non-symmetric.

All input probability distributions are constructed to be independent and thus uncorrelated. A total of 5,000 trials were sampled using Latin hypercube sampling, which is more efficient than random sampling.

Summary statistics for the RIC-M uncertainty analysis are presented in Table 4. The RIC-M mean net benefit ($6.097 million) is greater than the median ($5.666 million), indicating that the distribution is right-skewed. The RIC-M net-benefit interquartile range (IQR) is just over $3.2 million ($4.228 million to $7.537 million). The RIC-M net benefit 90 percent credible interval is just over $8.0 million ($2.710 million to $10.758 million).

Table 4. Summary Statistics for RIC-M Net Benefit Uncertainty Analysis

Mean	$	6,096,876
St. Dev.	$	2,558,042
5th Percentile	$	2,709,652
25th Percentile	$	4,227,678
Median	$	5,666,030
75th Percentile	$	7,537,495
95th Percentile	$	10,757,561

A histogram of the RIC-M net benefit (in 2017 dollars) based on N=5,000 trials is presented in Figure 2. The distribution is single-peaked and slightly skewed, with a long right tail. The corresponding cumulative distribution of the RIC-M net benefit (in 2017 dollars) is presented in Figure 3. The cumulative distribution graphically displays all percentiles as cumulative probabilities, including those summarized in Table 4. Both Figures 2 and 3 convey graphically the large RIC-M net benefit uncertainty.

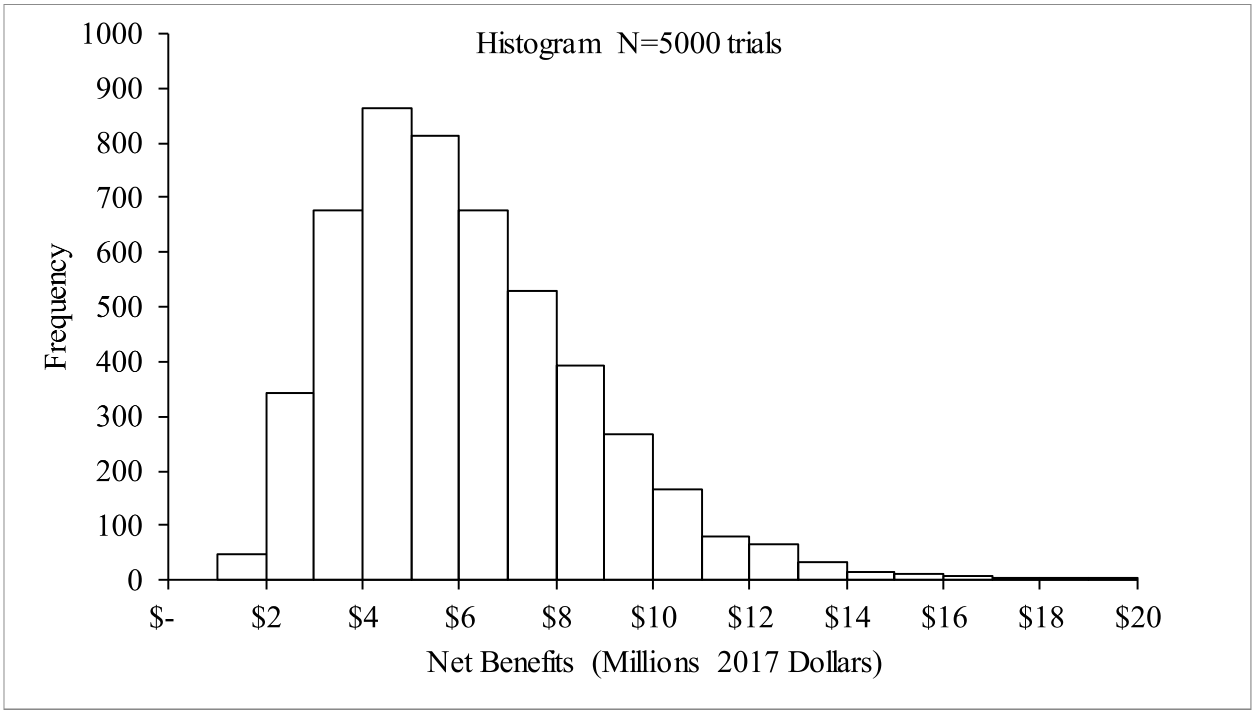

Figure 2. Histogram of RIC-M net benefit (N=5,000 trials)

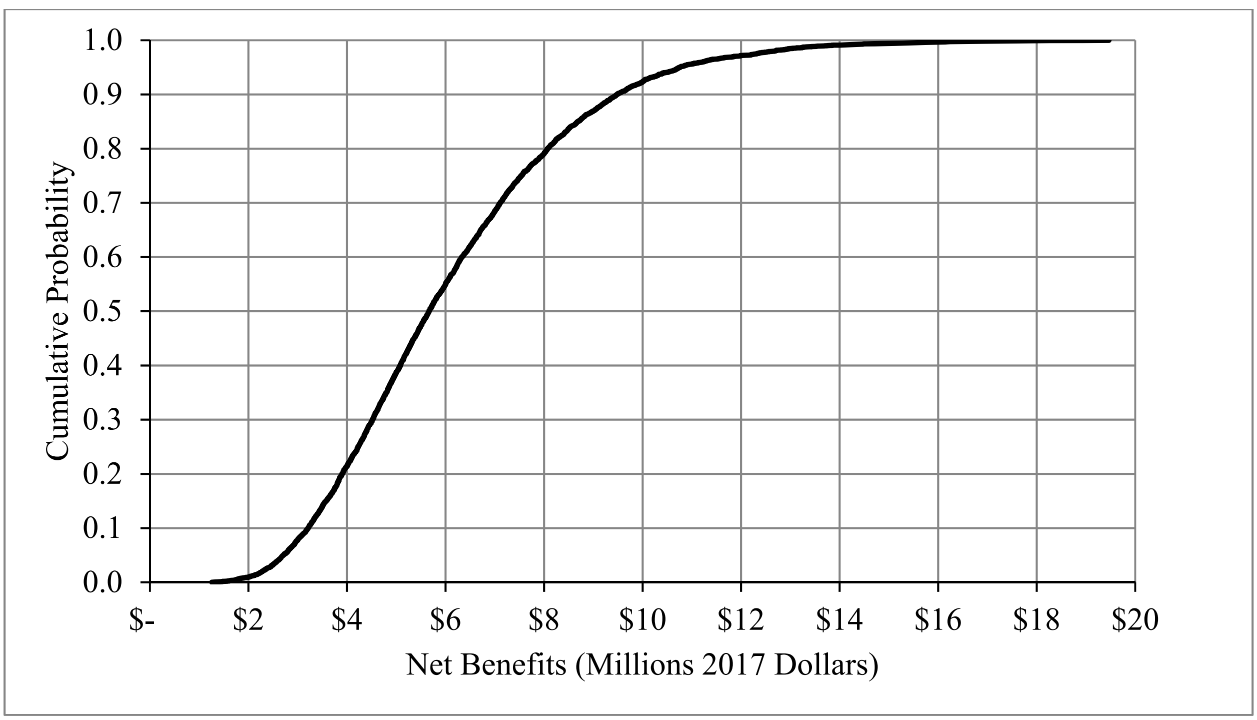

Figure 3. Cumulative distribution of RIC-M net benefit

8. Assumptions and Limitations

This analysis depends on a number of assumptions. First, the RIC-M benefit is conceptualized as the cost savings to first responder agencies of upgrading to a RIC-M versus purchasing a new base unit. The cost savings are discounted to account for reduced functionality, lifespan, and reliability, and cost savings are estimated as approximately equal to the cost of the RIC-M, less the distribution and royalty costs that are paid off the purchase price. No attempt was made to assess the extent of decreased performance or to model the total lifecycle cost of the RIC-M versus the purchase of a new unit. Ranges for the cost savings and benefit adjustment factor are speculative, and are included primarily to allow for sensitivity and uncertainty analyses spanning a range of possible values.

9. Additional Research

It would be helpful to know, for each RIC-M unit purchased, whether a new base unit would have been purchased if the RIC-M was not available. It would also be helpful to obtain expert judgements of the extent to which the RIC-M provides the same functionality and reliability as a new replacement base unit. As the tornado diagram indicates, RIC-M net benefits depend heavily on the benefit adjustment factor (the percentage of RIC-Ms purchased that would otherwise have required purchase of a new replacement unit) and the per-unit (discounted) cost savings.

10. References

Avtec, Inc. (2019). ASTRO Migration to IP with RIC-M. Retrieved September 30, 2019, from https://www.avtecinc.com/choosing-avtec/webinars/astro-migration-to-ip-with-ric-m

Radio Internet-Protocol Communications Module (RIC-M) Fact Sheet and Video (2019). Retrieved September 30, 2019, from https://www.dhs.gov/publication/st-ric-m

RIC-M Radio IP Communications Module (2019). Retrieved September 30, 2019, from https://www.acgsys.com/product/ric-m-radio-ip-communications-module/

Success Story: Radio Internet-Protocol Communications Module (RIC-M) (2019). Retrieved September 30, 2019, from https://www.federallabs.org/successes/success-stories/radio-internet-protocol-communications-module-ric-m

The New RIC-Mz — Better, Faster, More Secure (2019). Retrieved September 30, 2019, from www.christinewireless.com

Benefit-Cost Analysis of the Wildland Firefighter Advanced Personal Protection System (APPS)

Analysts: Stephanie Thrift and Detlof von Winterfeldt

December 10, 2019

1. Summary

Description. The Advanced Personal Protection System, Wildland Firefighter Personal Protection Equipment (APPS WLFF PPE, hereafter referred to as APPS) project was aimed at developing and evaluating a new protective garment system for wildland firefighters. The goals of the APPS project were to (1) improve heat absorption qualities and overall thermal protection, (2) generate a better heat loss rating to minimize heat stress, and (3) create more comfortable garments by enhancing the form and fit of the APPS.

Results. In the baseline, wildland firefighters face an annual fatality risk of $8.68E^{-05}$ and an annual injury risk of 4.59 percent. The cost analysis revealed that the APPS garments are more expensive by about $234 to $324 per garment system. While there was some uncertainty about the costs to the Department of Homeland Security Science and Technology Directorate (DHS S&T) from the APPS project, it turned out that these costs (estimated at $533,000 in 2017 dollars) had only a minor impact on total costs. Total costs were determined by using a market penetration rate of 5 percent over a five-year period, amounting to roughly $7 million. We analyzed the benefits of the APPS in terms of reducing fatality and injury risks. Based on technical estimates of the improved heat absorption rate (a 10 percent reduction) when using the APPS, we used a reduction of 10 percent in fatality and injury rates in the baseline. This resulted in total five-year benefits of about $19 million and a net present value (NPV) of about $12 million. In the base case, the benefit-cost ratio was estimated to be 2.7, and the return on investment was 174 percent over five years. An uncertainty analysis resulted in a range of NPV benefits, from $5 million (5th percentile) to $18 million (50th percentile) to $40 million (95th percentile). This large range was primarily due to the uncertainty about risk reduction and market penetration rates.

2. Description of the Project

The Advanced Personal Protection System, Wildland Firefighter Personal Protection Equipment (APPS) project was aimed at developing and evaluating a new protective garment system for wildland firefighters. The U.S. Army Natick Soldier Research, Development and Engineering Center (NSRDEC) in Natick, Massachusetts, with sponsorship from the Responder Technologies (R-Tech) Program of the Science and Technology Directorate at DHS and the Department of Agriculture's U.S. Forest Service (USFS), developed and tested the improved garment system between April 2011 and December 2013. The project and its results are described in detail in DHS S&T (2014a; 2014b).

The goals of the APPS project were to (1) improve heat absorption qualities and overall thermal protection, (2) generate a better heat loss rating to minimize heat stress, and (3) create more comfortable garments by enhancing the form and fit of the APPS. Through achieving these goals, the project sought to decrease the rates of heat injuries/fatalities and increase the possible work times of firefighters. This would ultimately promote operational effectiveness of wildland firefighters, thereby making the success of wildland firefighting missions more likely (DHS S&T, 2014a; 2014b).

Both objective and subjective evaluations were conducted to evaluate the APPS. Objective testing was strictly technical and quantitatively assessed fabric performance in terms of heat absorption coefficients. Subjective testing consisted of a "wear trial" in close cooperation with CAL FIRE, who provided personnel and equipment for testing the new garments in real firefighting situations. Both forms of testing of the APPS system confirmed that the project did achieve the aforementioned goals and therefore validated the project's application (DHS S&T, 2014a; 2014b).

In this benefit-cost analysis, we focus on the financial implications of reduced injuries due to the improved heat absorption of the advanced garment system. We evaluate the benefits resulting from fatality and injury reductions, and we compare the costs of the legacy PPE garments to the costs of the APPS garments.

3. Baseline Analysis

The baseline analysis consisted of assessing the wildland firefighters' risk of fatalities and injuries, with the intent to compare the performance in the baseline (with legacy garments) and the performance of the new advanced garments. We examined fatality data between 2007 and 2017 provided by the Federal Emergency Management Agency (FEMA, 2018). Injury data was provided in NFPA (2018).

We were unable to find the exact number of wildland firefighters, which is needed to determine the annual fatality and injury risk (see also Britton et al., 2013, who had a similar problem). To estimate the number of wildland firefighters, we used the percentage of the number of wildland firefighter fatalities and injuries as compared to the number of fatalities and injuries of all firefighters reported in FEMA (2018) and NFPA (2018). The fatality percentage is 9.5 percent, and the injury ratio is 15.8 percent. In the base case, we used the lower of these two percentages, rounded up to 10 percent. Applying this percentage to the 1,065,433 firefighters in the U.S. resulted in an estimate of 106,543 wildland firefighters. This number is used throughout this BCA.

Fatalities. FEMA (2018) lists nine distinct fatality types among wildland firefighters (see Table 1). These included aircraft accidents, burn-related deaths, falls, heart attacks and strokes, heat exhaustion, motor vehicle accidents, respiratory-related deaths, being struck by trees/debris, and other/unclear deaths. Five of these fatality types – burn-related deaths, heart attack and stroke, heat exhaustion, respiratory-related deaths, and other/unclear deaths – are potentially related to the garments that the firefighters wore at the time of their deaths.

Table 1. Firefighter Fatality Data

General Information		**Wildland Firefighter Fatalities**										
Fatality Type	*Garment-related?*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
Aircraft accident	No	1	10	5	-	-	6	-	2	-	-	-
Burn-related	Yes	-	1	-	-	4	-	19	5	3	-	1
Fall	No	-	2	-	-	-	-	-	1	-	1	1
Heart attack / stroke	Yes	1	5	4	5	2	4	9	1	4	2	1
Heat exhaustion	Yes	-	-		1	1	1	-	1	-	-	-
Motor vehicle accident	No	1	5	2	3	1	2	-	1	1	5	1
Respiratory-related	Yes	-	-	-	-	-	-	-	-	2	-	-
Struck by tree / debris	No	1	2	1	2	1	1	1	-	1	3	3
Other / unclear	No	1	1	4	-	1	1	2	-	1	4	3
Total Wildland Fatalities:		5	26	16	11	10	15	31	11	12	15	10
Garment-Related Wildland Fatalities:		2	7	8	6	8	6	30	7	10	6	5
Total Firefighter Fatalities:		118	118	90	87	83	81	106	91	90	89	87

Table 2 provides the resulting statistics analyzed from the fatality data in Table 1. Prior to 2015 (the year the new garments were introduced) there were, on average, 9.25 garment-related deaths per year. The individual wildland firefighter's risk of dying from garment-related causes is thus calculated to be 8.68E^{-05}.

Table 2. Analysis of Firefighter Fatality Data

Total Firefighter Fatality Yearly Average:	95
Wildland Firefighter Fatality Yearly Average:	15
Wildland Firefighter Fatality Related to Garments Yearly Average:	9.25
Total Average Firefighters:	1,065,433
Total Average Wildland Firefighters:	106,543
Annual Garment-related Fatality Risk	8.68E-05

Injuries. NFPA (2018) lists 10 distinct injury types among firefighters (both general and wildland, see Table 3). These included burns (fire/chemical), smoke/gas inhalation, other respiratory distress, burns and smoke inhalation, wound/cut/bleeding/bruise, dislocation or fracture, heart attack or stroke, strain/sprain/muscular pain, thermal stress, and other. Of these injury types, we excluded two that clearly did *not* relate to the garments that firefighters wore at the time of their injury: dislocation or fracture, and strain/sprain/muscular pain.

Table 3. Types of Firefighter Injuries

Injury Type	Garment-Related?	Cost of Injury
Burns (fire/chemical)	Yes	Medium - High
Smoke/gas inhalation	Yes	Medium
Other respiratory distress	Yes	Medium
Burns and smoke inhalation	Yes	High
Wound, cut, bleeding, bruise	Yes	Low
Dislocation, fracture	No	Medium
Heart attack or stroke	Yes	Extreme
Strain, sprain, muscular pain	No	Low
Thermal stress	Yes	High
Other	Yes	Low

We assume that up to 2015, these 106,543 wildland firefighters used either the legacy garment described below or similar garments. For the baseline, we can use the death and injury statistics involving the legacy garments. Between 2007 and 2015, there were, on average, 11,578 injuries per year related to wildland firefighters (see Table 4, FEMA, 2018; NFPA, 2018). Of these annual wildland firefighter deaths and injuries, 4,890 were related to garments. Therefore, the individual annual risk of injury of a wildland firefighter is 4.59 percent.

Table 4. Yearly Injury Report

Year	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	Average (2007-2014)
Number of Total Firefighter Injuries:	80,100	79,700	78,150	71,875	70,420	69,400	65,880	63,350	68,153	62,085	58,835	72,359
Number of Wildland Firefighter Injuries:	12,816	12,752	12,504	11,500	11,267	11,104	10,541	10,136	10,905	9,934	9,414	11,578
Number of Total Garment-Related Injuries	36,105	35,620	33,615	29,670	28,575	28,170	26,415	26,340	61,548	27,585	26,535	30,564
Number of Wildland Garment-Related Injuries:	5,777	5,699	5,378	4,747	4,572	4,507	4,226	4,214	9,848	4,414	4,246	4,890

Table 5. Analysis of Firefighter Injury Data

Number of Wildland Firefighters	106,543
Wildland Injury Related to Garments	4,890
Percent Annual Injuries	4.59%

4. Cost Analysis

We obtained cost estimates for the legacy and APPS garments by evaluating the costs of their components (pants, jackets, etc.). The Wildland Firefighter Personal Protective Equipment (PPE) Selection Guide (DHS S&T, 2014a; 2014b) was used to estimate the cost of the legacy system, and the Advanced Personal Protection System (APPS), Wildland Firefighter Personal Protection Equipment (WLFF PPE) Clothing System Program, Final Report was used to estimate the cost of the advanced system (DHS S&T, 2014a; 2014b).

After reviewing vendor sites, we estimated that the legacy system cost $947 (DHS, 2014; Kenyon Consumer Products, 2019; Swafford, 2017; FR Phase 1 Ribbed Boxer Brief, 2019; Flamestretch® Sock System, 2019; 1st Defense - Jacket, 2019; CX Urban Interface Fire Coat, 2019; Vector Wildland Fire Pant, 2019; Ethos Wildland Fire Pant, 2019; CX Urban Interface Vent Pants, 2019; 1st Defense – Trousers, 2019; Parrish, 2019). Table 6 displays the component cost breakdown of the legacy system from various vendors.

Table 6. Legacy System PPE Cost Data

PPE Item	*PVI*	*New Balance*	*CAL FIRE*	*Kenyon Consumer Products*	*California Prison Industry*	*Coaxsher*	*Massif*	Average
T-shirt price	-	-	-	$46.00	-	-	-	$46.00
Female sports bra price	-	$19.95	-	-	-	-	-	$19.95
Female undergarment price	-	$17.95	-	-	-	-	-	$17.95
Boxer price	$11.00	-	-	-	-	-	-	$11.00
Sock price	-	-	-	-	-	-	$69.99	$69.99
Response jacket price	-	-	$234.00	-	$181.00	$179.00	-	$198.00
Uniform pants price	-	-	-	-	-	$159.00	-	$159.00
Tactical pants price	-	-	-	-	-	$219.00	-	$219.00
Overpants price	-	-	$234.00	$184.00	-	$199.00	-	$205.67
							Total:	*$946.56*

We obtained cost estimates for the advanced system from several vendors and estimated a low-end average of $1,259 and a high-end of $1,349 (DHS, 2014; FR Phase 1 Advanced Cooling T-Shirt, 2019; Interface Pant, 2019; Men's Station Wear Base Layer, 2019; Swafford, 2017; 2 Pack of GI Sand 50/50 Boxers, 2019; Flamestretch® Sock System, 2019; Coats, 2019; Gen II Pants, 2019). Table 7 displays the component cost breakdown of the APPS system from various vendors.

Table 7. APPS PPE Cost Data

	Manufacturer							
PPE Item	*XGO*	*CrewBoss*	*Workrite*	*Elite Issue*	*Massif*	*New Balance*	**Low Average**	**High Average**
T-shirt price	$37.50	-	$63.00	-	-	-	$50.25	$50.25
Female sports bra price	-	-	-	-	-	$19.95	$19.95	$19.95
Female undergarment price	-	-	-	-	-	$17.95	$17.95	$17.95
Boxer price	-	-	-	$8.99	-	-	$8.99	$8.99
Sock price	-	-	-	-	$69.99	-	$69.99	$69.99
Response jacket price	-	$270-$312	$242.00	-	-	-	$256.00	$277.00
Uniform pants price	-	$220.00	232-313.20	-	-	-	$226.00	$266.50
Tactical pants price	-	$229.00	231-288	-	-	-	$230.00	$258.50
Overpants price	-	$380.00	-	-	-	-	$380.00	$380.00
						Total:	*$1,259.13*	*$1,349.13*

We are primarily interested in the difference in price between the legacy garments and the advanced garments, which ranges from $234.57 to $324.57 (see Table 8). For the base case analysis, we used the average of these two differences, or $279.

Table 8. Legacy vs. APPS Cost Differences

Garment Type	*Low Average APPS Cost*	*High Average APPS Cost*	*Average Legacy System Cost*	*Low Average Difference*	*High Average Difference*
T-shirt price	$50.25	$50.25	$46.00	$4.25	$4.25
Female sports bra price	$19.95	$19.95	$19.95	$0.00	$0.00
Female undergarment price	$17.95	$17.95	$17.95	$0.00	$0.00
Boxer price	$8.99	$8.99	$11.00	-$2.01	-$2.01
Sock price	$69.99	$69.99	$69.99	$0.00	$0.00
Response jacket price	$256.00	$277.00	$198.00	$58.00	$79.00
Uniform pants price	$226.00	$266.50	$226.00	$0.00	$40.50
Tactical pants price	$230.00	$258.50	$230.00	$0.00	$28.50
Overpants price	$380.00	$380.00	$205.67	$174.33	$174.33
			Total Difference:	*$234.57*	*$324.57*

We combined this per-unit cost with a market penetration analysis in the base case, in which we assumed a 5 percent per year market penetration for 106,543 wildland firefighters for the first five years (2015 to 2019). After this, the garments purchased in 2015 would need to be replaced, and the cycle begins anew. We ignored additional garment purchases after the first 5 years, because there likely will be new products and developments after this initial cycle. With these assumptions, there will be a total of 24,107 purchases in the first 5 years, thus costing $6,529,384 more (in 2017 dollars) than the legacy PPE system (see Table 9).

Table 9. Total Five-Year Cost Differences Between Legacy and APPS Garments[4]

Year	Sales/Yr.	Cost Diff*	Cost Diff x Sales
2015	5328	$272	$1,448,722
2016	5062	$263	$1,329,495
2017	**4809**	**$268**	**$1,289,544**
2018	4568	$274	$1,250,793
2019	4340	$279	$1,210,830
Total	**24,107**		**$6,529,384**

[4] Cost differences are inflation adjusted. Due to rounding of the numbers in this and other tables, the calculated numbers do not always match the numbers when checked with separate calculations using the numbers in the tables.

In addition to the increased purchase cost of the APPS garment, DHS S&T also had to cover the costs of the project (i.e., the development of the advanced garments), which lasted from April 2011 to December 2013. We were unable to ascertain the precise costs of this project, so we used the median cost of several projects funded by S&T during the same time period, which was about $500,000. Using inflation to 2017 and discounting down from 2019, we estimate the equivalent 2017 cost to be $533,000 (see Table 10). Therefore, the total cost of the project (including implementation for five years) is estimated at $7,062,384.

Table 10. S&T Project Cost

Year	Nominal $	2017 $
2011	$ 100,000	$ 109,000
2012	$ 200,000	$ 214,000
2013	$ 200,000	$ 210,000
Total S&T Cost	**$ 500,000**	**$ 533,000**

5. Benefit Analysis

The main benefit of the advanced garments considered in this BCA is the reduction of injury costs. According to the U.S. Army Natick Center (2014), the new garments lower the heat absorption coefficients by about 10 percent. As a first cut, it is reasonable to apply this percentage to a percentage reduction in fatalities and injuries, especially as they relate to heat stress injuries like heart attacks and strokes. To estimate the risk reduction benefits, we also need to estimate the number of APPS garments sold to firefighters. Unfortunately, the vendors did not provide us with sales data, which they consider to be proprietary information. Instead of actual sales data, we used a market penetration model with a sales estimate of 5 percent of the wildland firefighter population per year. Table 11 shows the market penetration estimates for the first five years after the APPS were developed and evaluated. Over these five years, the total number of firefighters who will wear the APPS garments is 24,107, or 23 percent of all wildland firefighters (second column of Table 11). Applying the $8.68E^{-05}$ annual individual fatality rate results in the total number of expected fatalities for each year (third column of Table 11). Viscusi (2009), Merrill (2017), and Knieser and Viscusi (2019) estimate the statistical value of a life at about $10 million. Combining the annual number of expected fatalities with the $10 million value of a statistical life results in the annual expected costs due to wildland firefighter fatalities (fourth column of Table 11). Due to the 10 percent reduction of fatality risks when wearing the APPS, we can determine the reduced expected costs, which are shown in the fifth (nominal) and sixth (in 2017 dollars) columns of Table 11. Thus, the benefits of the APPS garments in reducing fatality risks is $10.37 million. We assume that five years is all the protection afforded for each wildland firefighter wearing the new garments. No additional costs and benefits are considered after these five years, since it is likely that new garments with a new cost and benefits cycle will replace the APPS PPE by then.

Table 11. Market Penetration, Deaths, Costs, and Cost Reduction with APPS

Market Penetration: 5%/year; Value of Statistical Life: $10m; 10% Reduced Cost					
Year	**APPS Sales**	**Deaths/year**	**Cost for 5 years**	**Reduced Cost**	**2017 Dollars**
2015	5,327	0.46	23,119,831	$ 2,311,983	$ 2,244,644
2016	5,061	0.44	21,963,839	$ 2,196,384	$ 2,045,652
2017	4,808	0.42	20,865,647	$ 2,086,565	$ 2,086,565
2018	4,567	0.40	19,822,365	$ 1,982,237	$ 2,030,603
2019	4,339	0.38	18,831,247	$ 1,883,125	$ 1,959,203
Total	***24,102***	***2***	***104,602,930***	***$ 10,460,293***	**$ 10,366,666**

The estimation of injury reduction benefits is more complicated, since different injuries have different costs. To gain a more precise understanding of these financial benefits, we examined the average cost of treating each injury type (Sahin et al., 2011; Fife et al., 2012; “Broken Bone Costs,” 2017; Vernon, 2010; Shah et al., 2016; “Heat Stress,” 2014). We segmented costs into four categories and used the midpoints of these ranges for the base case analysis (see Table 12):

- “Low” costs ranged from $0-$5,000
- “Medium” costs ranged from $5,001-$15,000
- “High” costs ranged from $15,001-$50,000
- “Extreme” costs constituted anything above $50,000

Table 12. Wildland Firefighter Injuries and Associated Costs

Injury Type	*Garment-Related?*	*AverageInjuries (2007-2014)*	*Qualitative Severity*	*Low Cost*	*High Cost*	*Basecase Ciost*	*Expected Cost*
Burns (fire/chemical)	Yes	404	Medium - High	$ 5,000	$ 50,000	$ 27,500	$ 2,270
Smoke/gas inhalation	Yes	331	Medium	$ 5,000	$ 15,000	$ 10,000	$ 678
Other respiratory distress	Yes	165	Medium	$ 5,000	$ 15,000	$ 10,000	$ 337
Burns and smoke inalation	Yes	95	High	$ 15,000	$ 50,000	$ 32,500	$ 631
Wound, cut, bleeding, bruise	Yes	1807	Low	$ -	$ 5,000	$ 2,500	$ 924
Dislocation, fracture	No	314	Medium	$ 5,000	$ 15,000	$ 10,000	$ -
Heart attack or stroke	Yes	138	Extreme	$ 50,000	$ 500,000	$ 275,000	$ 7,744
Strain, sprain, muscular pain	No	6373	Low	$ -	$ 5,000	$ 2,500	$ -
Thermal Stress	Yes	428	High	$ 15,000	$ 50,000	$ 32,500	$ 2,842
Other	Yes	1523	Low	$ -	$ 5,000	$ 2,500	$ 778
Total Garment Related Injuries/Year		4890		**Total Expected Cost of Injuries/Year**			**$ 16,204**

Thus, the total annual expected cost of garment-related injuries is $16,204. Using these total annual costs of injuries, a 5 percent market penetration rate of the APPS PPE, a useful life of five years for the APPS, and a 10 percent reduction in injury risks, we arrived at a total benefit (reduction of injury cost) of $8,982,388 (see Table 13). Combining the benefits of reductions of fatalities and of injuries, we arrive at a total benefit of $19,349,054.

Table 13. Market Penetration, Injuries, Injury Cost, and Cost Reduction with APPS

Market Penetration: 5%/year; Injury Cost: $16.6K, 10% Reduced Cost					
Year	With APPS	Injuries/Year	Cost for 5 Years	Reduced Cost	2017 Dollars
2015	5,327	245	19,810,701	$ 1,981,070	$ 1,923,369
2016	5,061	232	18,820,166	$ 1,882,017	$ 1,845,114
2017	4,808	221	17,879,158	$ 1,787,916	$ 1,787,916
2018	4,567	210	16,985,200	$ 1,698,520	$ 1,739,964
2019	4,339	199	16,135,940	$ 1,613,594	$ 1,686,025
Total	***24,102***	***1,106***	***89,631,166***	***$ 8,963,117***	***$ 8,982,388***

Table 14 shows both the inputs (upper part) and the outputs of the benefit-cost calculations.

Table 14. Inputs and Outputs of the Benefit-Cost Analysis

Number of Wildland Firefighters	106,543
Cost Difference (APP PPE - Legacy Garment)	$279
S&T Project Cost	$533,000
Annual Fatality Risk (Garment Related)	8.68E-05
Annual Injury Risk (Garment Related)	4.59%
Reduction of Fatality and Injury Risks	10%
Cost of Injury	$16,204
Cost of Fatality	$10,000,000
Market Penetration/Year	5%
Cost of Difference (APP-Legacy Garment)	$6,529,384
S&T Cost	$533,000
Total Cost	$7,062,384
Total Benefit	$19,349,054
Net Present Value	$12,286,670
BCR	2.7
ROI	174%

6. Net Benefits, Benefit-Cost Ratio, and Return on Investment

Using the estimates of costs ($7,062,384) and benefits ($19,349,054) in Table 14, we determine that the net benefits (NPV of benefits–NPV of costs) are $12,286,670 in the base case. The benefit-cost ratio is 2.7 and the return on investment is 174 percent over five years. If we ignore the reduction of fatality risks and calculate the benefits only for the reduction of injury risks, the total benefits are $8,982,388, the net benefits are $1,920,004, the BCR is 1.3, and the ROI is 27 percent.

7. Sensitivity and Uncertainty Analysis

Break-even analysis. Two key uncertain parameters are the reduction of injury and fatality risks due to the APPS and the market penetration rate. The break-even point (NPV=$0) is reached when the reduction of fatality and injury risks is about 3.65 percent or when the market penetration rate is 1.7 percent. Both numbers are at the very low end of plausible estimates and thus, the break-even analysis suggests that there is a high likelihood of a positive NPV.

Sensitivity analysis. A tornado analysis (see Clemen and Reilly, 2015; Treeplan, 2019a) of the input variables that influence the NPV, BCR, and ROI outputs are:

1. S&T project cost
2. Cost difference between APPS and legacy garments
3. Annual fatality risk (garment-related)
4. Annual injury risk (garment-related)
5. Reduction of fatality and injury risks
6. Cost of a fatality
7. Cost of an injury
8. Market penetration rate/year

The ranges for these input variables are shown in Table 15.

Table 15. Ranges of Input Variables for the Benefit-Cost Analysis

	Low	Base	High
S&T Project Cost	$250,000	$ 500,000	$1,000,000
Cost difference (APPS - Legacy Garment)	$234	$ 279	$334
Annual Fatality Risk (Garment Related)	5.00E-05	8.7E-05	1.00E-04
Annual Injury Risk (Garment Related)	3%	4.59%	10%
Reduction of Fatality and Injury Risks	5%	10%	20%
Cost of Injury	$10,000.00	$16,204.00	$20,000.00
Cost of Fatality	$8,000,000	$ 10,000,000	$12,000,000
Market Penetration/Year	2.50%	5%	10%

The resulting tornado diagram is shown in Figure 1, suggesting that the most important input variables are (in order): the reduction of injury and fatality risk when using the APPS, the APPS market penetration rate, and the annual fatality and injury risks. Interestingly, the S&T project costs do not have a large impact within the range of plausible costs because the total costs are dominated by the cost differential between the APPS garments and the legacy garments.

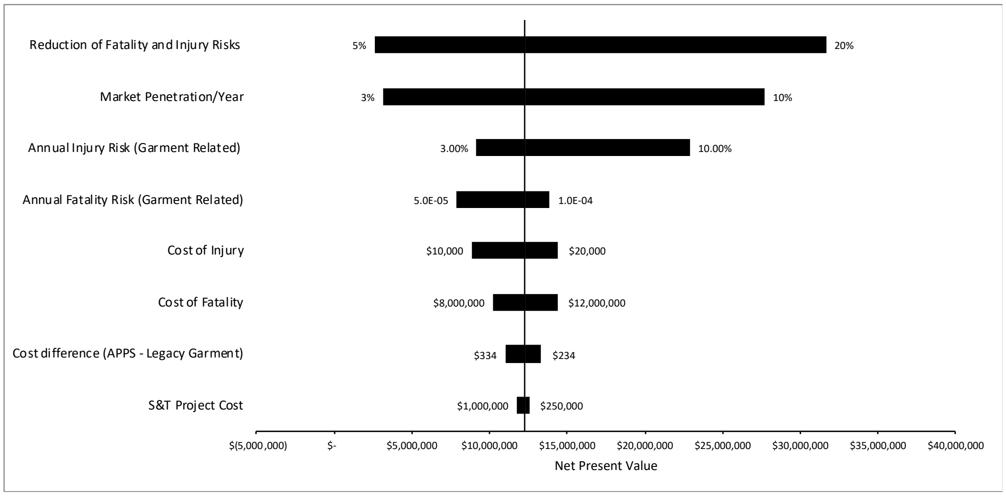

Figure 1. Tornado analysis of input variables to the benefits model

Probabilistic simulation. We assigned triangular distributions to the input parameters shown in Table 15 (Treeplan, 2019b). Using these input distributions, a probabilistic simulation showed a large variability in net present values, ranging from a 5th percentile of $5,382,882 to a median of $18,095,908 to a 95th percentile of $40,595,460 (see Figure 2 and Table 16).

Table 16. Simulation Statistics of the Net Present Value

Mean	$ 19,873,826
Standard Deviation	$ 10,864,501
5th Percentile	$ 5,382,882
25th Percentile	$ 11,982,629
50th Percentile	$ 18,095,908
75th Percentile	$ 25,718,583
95th Percentile	$ 40,595,460

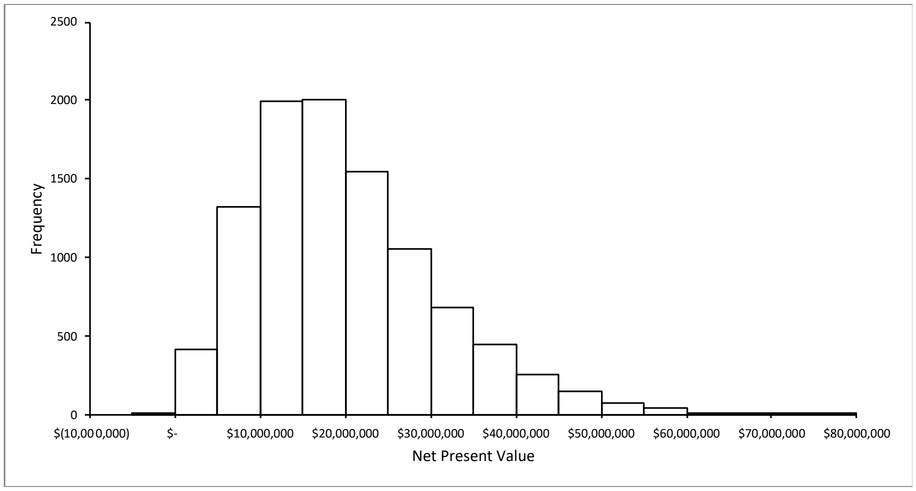

Figure 2. Probability distribution over net present value

This is a very large range, primarily due to the uncertainty about the fatality and injury risks, the reduction of these risks, and the market penetration of the APPS.

8. Assumptions and Limitations

This BCA showed a positive NPV, as well as a reasonably high BCR and ROI, as a result of the APPS project and the resulting increased use of APPS. When using both fatality and injury risk reductions, the NPV is positive for all plausible input parameters. When using only injuries, the NPV, BCR, and ROI estimates are reduced substantially, and, with some parameters, the NPV is negative due to the cost difference between the APPS and the legacy garments.

The main uncertain assumptions are about the reduction of fatality and injury risks and the market penetration rate. It should not be difficult to narrow down the ranges of the fatality and injury risks by additional analyses of existing data. In fact, our analysis may have overestimated the range of uncertainties in these estimates. Estimating the reduction of these risks due to the APPS is a more challenging task. In this analysis, we assumed that the reduction in risk is proportional to the reduction of the heat absorption coefficient, but this needs to be confirmed. We were unable to obtain estimates of actual sales due to proprietary data by the vendors. We used a market penetration model that could be replaced by actual sales data.

9. Additional Research

One cost estimate that is usually readily available is the project cost, which was incurred by the S&T Directorate of DHS. Due to changing leadership at the project management level, we were unable to ascertain these costs and had to make rough estimates based on the costs of similar FRG projects. Additional interviews with S&T managers may refine our estimates somewhat. Fortunately, even a large range of costs (from $250,000 to $1 million) played only a minor role in determining the net present value, BCR, and ROI.

To obtain better estimates of the reduction of fatality and injury risks, a statistical analysis of these risks with and without APPS would be useful. In addition, an expert elicitation workshop that focuses on the relationship between the heat absorption improvement and the reduction in fatality and injury risks could be conducted.

Finally, actual sales data should replace our estimates of sales using a market penetration model. We are in contact with market data analysts to provide such data without obtaining proprietary sales data by the vendors.

Similarly, the market penetration rate could be replaced with actual market penetration data. Unfortunately, the vendors of APPS were unwilling to provide this data. We believe that the market penetration estimates that we used are on the low side of how many APPS were actually sold, but we were unable to verify this.

An interesting by-product of this analysis was that the BCR and the ROI estimates were quite stable, even with large swings of the NPV. This occurred because with increased benefits, there also is an increase in cost, particularly when more APPS are sold.

10. References

1st Defense-NFPA 1977:2016 Wildland Jacket. (2019). Retrieved October 08, 2019, from https://catalog.calpia.ca.gov/product/1st-defense-nfpa-19772016-wildland-jacket-1500/

1st Defense-NFPA 1977:2016 Wildland Trousers. (2019). Retrieved October 08, 2019, from https://catalog.calpia.ca.gov/product/1st-defense-nfpa-19772016-wildland-trousers-2235/

2 Pack of GI Sand 50/50 Boxers. (2019.). Retrieved October 08, 2019, from https://www.armynavysales.com/2-pack-of-gi-sand-50-50-boxers.html

Britton, C., Lynch, C.F, Torner, J., & Peek-Asa, C. (2013). Fire characteristics associated with firefighter injury on large federal wildland fires. Annals of Epidemiology, 23, 37-41.

Broken bone costs and how to pay for them. (2017, December 6). Retrieved November 4, 2019, from https://www.lendingpoint.com/blog/broken-arm-or-broken-wrist-what-it-costs-and-how-to-pay-for-it/.

Clemen, R. & Reilly, T. Making hard decisions. (2014). Mason, OH: South-Western and Cengage.

Coats. (2019). Retrieved October 08, 2019, from https://crewboss.store/collections/coats

CX Urban Interface Fire Coat. (2019). Retrieved October 08, 2019, from http://www.coaxsher.com/CX-Urban-Interface-Coat-p/fc102.htm

CX Urban Interface Vent Pants. (2019). Retrieved October 08, 2019, from http://www.coaxsher.com/CX-Urban-Interface-Vent-Pants-p/fc202.htm

DHS S&T. (2014a, June). Wildland Firefighter Personal Protective Equipment (PPE) Selection Guide. Retrieved October 08, 2019, from https://www.dhs.gov/sites/default/files/publications/Wild-FF-PPE-SG_0614-508.pdf

DHS S&T, U.S. Army Natick Soldier Research, Development and Engineering Center, & Responder Technologies (R-Tech) Program. (2014b, June 30). Advanced Personal Protection System (APPS), Wildland Firefighter Personal Protection Equipment (WLFF PPE) Clothing System Program, Final Report. Retrieved from https://www.dhs.gov/sites/default/files/publications/APPS - WLFF PPE FINAL REPORT.pdf

Ethos Wildland Fire Pant. (2019). Retrieved October 08, 2019, from http://www.coaxsher.com/Ethos-Wildland-Fire-Pant-p/fc207.htm

FEMA. (2018, September). Firefighter Fatalities in the United States in 2017. Retrieved October 07, 2019, from https://www.usfa.fema.gov/downloads/pdf/publications/ff_fat17.pdf

Fife, C. E., Carter, M. J., Walker, D., & Thomson, B. (2012, January 1). Wound Care Outcomes and Associated Cost Among Patients Treated in US Outpatient Wound Centers: Data From the US Wound Registry. Retrieved November 4, 2019, from https://www.woundsresearch.com/article/wound-care-outcomes-and-associated-cost-among-patients-treated-us-outpatient-wound-centers-d

Flamestretch® Sock System (FR). (2019). Retrieved October 08, 2019, from https://www.massif.com/shop/accessories/flamestretch-sock-system.html

FR Phase 1 Advanced Cooling T-Shirt. (2019). Retrieved October 08, 2019, from https://www.proxgo.com/collections/fr-phase-1/products/mens-fr-relaxed-fit-t-shirt-with-ac

FR Phase 1 Ribbed Boxer Brief. (2019). Retrieved October 08, 2019, from https://www.proxgo.com/products/1fr13xwf-boxer-briefs?_pos=2&_sid=50a729f9d&_ss=r

Gen II Pants. (2019). Retrieved October 08, 2019, from https://crewboss.store/collections/gen-ii-pants

Heat Stress. (2014). Retrieved November 4, 2019, from https://www.lawsonproducts.com/pdfs/PIRSF_Heat_Stress_PI.pdf.

Knieser, T.J. & Viscusi, W.K. (2019). The Value of a Statistical Life. *Vanderbilt Law Research Paper No. 19-15*. 45 Pages Posted: 16 May 2019. Forthcoming, *Oxford Research Encyclopedia of Economics and Finance.*

Interface Pant. (2019). Retrieved October 08, 2019, from https://crewboss.store/collections/wildland-pants/products/interface-pant-6-0oz-nomex

Kenyon Consumer Products. (2019). FR Garments. Retrieved October 08, 2019, from https://www.kenyon.us/collections/fr-garments

Men's Station Wear Base Layer Tee (Athletic Style). (2019). Retrieved October 08, 2019, from https://www.bulwark.com/mens-station-wear-base-layer-tee-%28athletic-style%29/FT36.html

Merrill, D. (2017). No one values your life more than the federal government. Bloomberg, October 19.

NFPA. (2018, November). United States Firefighter Injuries 2017. Retrieved October 07, 2019, from https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Emergency-responders/osffinjuries.pdf

Parrish, J. (2019, September 18). CAL FIRE PPE Prices [E-mail to the author].

Sahin, I., Ozturk, S., Alhan, D., Açikel, C., & Isik, S. (2011, March 31). Cost analysis of acute burn patients treated in a burn centre: the Gulhane experience. Retrieved November 4, 2019, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3187939/.

Shah, S., Thomas, A. C., Noone, J. M., Blanchette, C. M., & Wikstrom, E. A. (2016). Incidence and Cost of Ankle Sprains in United States Emergency Departments. Retrieved November 4, 2019, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5089353/.

Swafford, J., Jr. (2017, August 08). Review: New Balance introduces flame resistant sports bra and boy shorts. Retrieved October 08, 2019, from https://www.militarytimes.com/off-duty/military-fitness/2013/08/15/review-new-balance-introduces-flame-resistant-sports-bra-and-boy-shorts/

Treeplan. (2019a). Sensit Guide, 2017. www.treeplan.com. Last accessed November 5, 2019

Treeplan. (2019b). SimVoi-308-Guide, 2017. www.treeplan.com. Last accessed November 5, 2019

U.S. Army Natick Center. (2014). Advanced Personal Protection System (APPS), Wildland Firefighter Personal Protection Equipment (WLFF PPE) Clothing System. Final Report, U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA.

Vector Wildland Fire Pant. (2019). Retrieved October 08, 2019, from http://www.coaxsher.com/Vector-Wildland-Fire-Pant-p/fc208.htm

Vernon, S. (2010, April 23). How Much Would a Heart Attack Cost You? Retrieved November 4, 2019, from https://www.cbsnews.com/news/how-much-would-a-heart-attack-cost-you/.

Viscusi, W. K. (2009). Valuing risks of death from terrorism and natural disasters. *Journal of Risk and Uncertainty*, 38(3), 191-213.

Benefit-Cost Analysis of the National Resilience Standards for Floodproofing (Barrier) Products[5]

Analysts: Dan Wei, Adam Rose, and Juan Machado

October 2019

1. Summary

Description. The National Resilience Standards Program for floodproofing products combines aspects of setting standards and protocols for testing and certifying floodproofing products and their adoption. Since 2012, DHS S&T has collaborated with the Association of State Floodplain Managers (ASFPM), U.S. Army Corps of Engineers (USACE), and the private product certification firm FM Approvals to expand the existing National Flood Barrier Testing and Certification Program (NFBTCP) and to develop rigorous testing standards and certification protocols for new floodproofing products. The goal is to set targets for improvement of flood barriers in terms of quality and effectiveness, in this case the ability to prevent floodwaters up to four feet in height from entering structures. The Program includes products that fall into six broad product categories – temporary barriers, semi-permanent barriers, closures devices, backwater valves, sealants, and mitigation pumps – which are expected to provide reductions in flood losses to residential, commercial, agricultural, and industrial properties. So far, 13 products under the categories of temporary barriers and closures devices have been certified under this Program (DHS, 2019). It is expected that the availability of these products and the certification of their quality will induce potential users to adopt them. This pertains to both users who are already purchasing floodproofing products of lower quality/effectiveness and those who previously had not adopted any such products.

Results. The estimated total program cost of the Floodproofing Product Standards and Certification is about $1.648 million (in 2017 dollars). This includes the internal coordination costs between the organizations that oversee this Program and the manufacturers of the dry floodproofing products being tested and certified, the Program outreach costs, the water-related

[5] We acknowledge the valuable input by Drew Whitehair, Chad Berginnis, and David Alexander. We also appreciate the research assistance of Peter Eyre, Shannon Prier, and Konstantinos Papaefthymiou. The authors are solely responsible for any errors or omissions.

and material-related test costs, and the testing equipment costs. Of these various types of costs, the water-related and material-related testing costs are paid by the manufacturers.

There are three potential benefits of the Program: 1) increased quality of flood protection of the certified floodproofing products; 2) increased adoption of dry floodproofing products because of the Program; and 3) potentially more cost-effective (lower-cost) floodproofing products. We estimate the benefits primarily based on the assumption of wider adoption of floodproofing products and the potential property losses that can be avoided. We also obtained the cost information of the certified products so that the effect of the relatively lower costs of these products is also taken into consideration. Under the Base Case assumption, the Program is estimated to result in $272.48 million net benefits over a 10-year time horizon, which substantially exceeds the Program-related costs of $1.648 million. The benefit-to-cost ratio for the implementation of the Program (including the installed costs of the products) is 12.9, and the return on investment (ROI) is 1,192 percent.

The estimated net benefits associated with the National Floodproofing Products Standards and Certification Program are sensitive to some of the assumed parameters. The largest uncertainty comes from the assumptions with respect to the increased adoptions of dry floodproofing products because of the Program. Other important variables include annual losses from flood events per residential building and the percent property losses that can be reduced by adopting dry floodproofing. The uncertainty analyses on these variables, using a Monte Carlo simulation, resulted in a mean net benefit of $447.7 million, with a 5th percentile of $154.1 million and a 95th percentile of $861.1 million.

2. Description of the Project

Problem context. Substantial damages have been caused by floods in the U.S., amounting to an average annual economic loss of nearly $8 billion per year over the past three decades (Lightbody, 2017; Nunez, 2019). Despite increased investment in flood control, the combination of increasing extreme storm events, changes in land use, and a build-up of the number of assets at risk has resulted in an increasing trend of economic losses caused by floods. Based on a recent study by the Congressional Budget Office, the expected damages from storm-related flooding in the U.S. could reach as high as $20 billion annually in the near future, among which nearly 75 percent will occur in the residential sector (CBO, 2019).

The demand for reliable mitigation measures, such as floodproofing products, has increased in recent years with the anticipated increase in the number and severity of flooding disasters. There are hundreds of floodproofing products available in the market, such as temporary and semi-permanent barriers, closure devices, sealants, and mitigation pumps (DHS, 2019). However, it is essential to provide the public more information on their quality in order to promote their adoption.

National Resilience Standards for Floodproofing (Barrier) Products. The main purpose of the National Resilience Standards Program for floodproofing products is to establish new standards and protocols for testing and certifying new floodproofing (barrier) product categories (DHS, 2019).[6] It is expected that the increased awareness of the availability of high quality and reliable floodproofing products will increase the adoption of these products in flood-prone communities. This can potentially include both users who are already purchasing floodproofing products of lower quality/effectiveness and those who previously had not adopted any such products.

In order to develop these new standards, DHS S&T has collaborated with the Association of State Floodplain Managers (ASFPM), U.S. Army Corps of Engineers (USACE), and FM Approvals[7] to expand the existing National Flood Barrier Testing and Certification Program (NFBTCP) to develop rigorous testing standards and certification protocols for the new floodproofing products (ASFPM, 2016).

The Program includes products that fall into the following six broad product categories: temporary barriers, semi-permanent barriers, closures devices, backwater valves, sealants, and mitigation pumps, which are expected to provide reductions in flood losses to residential, commercial, agricultural, and industrial properties. Currently, however, the Program is only certifying temporary barriers, closures, backwater valves and mitigation pumps (ASFPM, 2019). Thirteen products under the categories of temporary barriers and closures devices have been certified so far and are presented in Table 0 below. The Program originally designed three

[6] The term resilience is used in the study as a synonym for mitigation, primarily intended to prevent property damage. Many analysts prefer to reserve the term for tactics to prevent business interruption and to promote recovery once the property damage has taken place (see, e.g., Cutter, 2016; Rose, 2017).
[7] FM Approvals is a business unit of FM Global, a U.S. business property insurance company. FM Approvals provides third-party testing and certification services on property loss prevention products (FM Approvals, 2019).

possible certification levels (silver, gold and platinum) based on maximum depth of hydrostatic water testing. However, given that most of the businesses would choose to apply for the highest certification level (which will provide them the highest credential in marketing), it is likely that the program will phase out the three certification levels and only provide certification for testing that corresponds to the platinum waterproofing level (against floodwaters up to four feet in height).

Table 0. List of Certified Floodproofing Products

Product Name	Manufacturer	Product Description
Tiger Dam Perimeter Flood Barrier	TIGER DAMS (https://usfloodcontrol.com/products/)	2-1 Stackable Configuration 19" Diameter & Single Tube Configuration 19", 24", & 36"
US Flood Control 42 Inch	TIGER DAMS (https://usfloodcontrol.com/products/)	Reusable Temporary Perimeter Barrier
MegaSecur Water-Gate WL	MegaSecur (http://megasecur.com/water-gate-wl)	Water Gate
AquaFence Model V1200	AquaFence (https://www.aquafence.com/)	Wall Panels
Dai Chen DCAM-01	DAI CHEN (http://en.daichen.com.tw/index.html)	Combined Watertight Gate
Dai Chen DCAMW-02	DAI CHEN (http://en.daichen.com.tw/index.html)	Multi-Function Flood-Proof Watertight Gate
Dai Chen DC SD-03	DAI CHEN (http://en.daichen.com.tw/index.html)	Manual Ditch Watertight Gate
Presray FastLog Standard or Heavey Duty	PRESRAY (http://www.presray.com/flood-protection/stackable-flood-barrier-fastlogs)	Stackable Flood Barrier
Presray FB44	PRESRAY (http://www.presray.com/flood-protection/hinged-floodgate-fb44)	Floodgate
Presray FB33	PRESRAY (http://www.presray.com/flood-protection/adjustable-flood-barrier-fb33)	Adjustable Flood Protection Door Barrier
Presray FB22	PRESRAY (http://www.presray.com/flood-protection/removeable-flood-barrier-fb22)	Aluminum Panel
P S Doors FP-530FM	PS Flood Barriers (https://www.psfloodbarriers.com/product/hydrodefense-flood-plank/)	Flood Plank
P S Doors PD-520X	PS Flood Barriers (https://www.psfloodbarriers.com/product/pedestrian-flood-door-single/)	Single or Double Pedestrian Door

Source: National Flood Barrier Testing & Certification Program (2019).

3. Baseline Analysis

Appendix Table A-1 presents a summary of the literature reviewed on the adoption rates of dry floodproofing measures. Most estimates of the adoption of dry floodproofing measures found in the existing literature are based on surveys of households and are used to explore the socio-economic and risk determinants of mitigation behavior. The adoption estimates are not easily comparable across studies as the surveys vary in terms of sampled respondents (e.g., all residents or only homeowners) and households (e.g., across a wide area or only in flood-prone areas), as well as how they define mitigation measures.

The most relevant adoption estimates are found in Botzen et al. (2019) and Brody et al. (2017), two recent works that survey households in different areas of the United States. Botzen et al. (2019) found that approximately 25 percent of New York City homeowners living in flood-prone areas owned flood shields or sand bags before the last major flood event—Hurricane Sandy for most homeowners—and that the adoption rate increased to 32 percent following the event.

Brody et al. (2017) surveyed four different Florida and Texas coastal communities. Unlike Botzen et al., the authors did not exclusively survey households in flood-prone areas but included roughly equal numbers of houses located in 100-year floodplains, 500-year floodplains, and minimal flood hazard areas. They found that 2.6 percent of the households surveyed had implemented some type of dry floodproofing technique, whether that was adding a waterproof veneer to exterior walls or sealing openings with shields or sandbags. The discrepancy between the estimates presented in Botzen et al. (2019) and Brody et al. (2017) are not entirely surprising, as the latter study also includes households at a lower risk of flooding.

Four studies presented estimates for dry floodproofing adoption in different regions of Germany prone to riverine flooding. Bubeck et al. (2013) found that 17 percent of flood-prone households located along the Rhine had fixed or mobile flood barriers. Grothmann and Reusswig (2006) found that 38 percent of respondents living in flood-prone homes in Cologne had purchased protective barriers for windows and doors or pumps. Kreibich et al. (2005) surveyed residents affected by the 2002 flood at the river Elbe and found that 7 percent owned water barriers before the flood, and 27 percent owned them after. Finally, Osberghaus (2017) includes adoption estimates for 7,400 households across Germany, but the mitigation measures the respondents were asked about do not correspond to the type of products considered in this analysis.

The literature reviewed shows that adoption rates of dry floodproofing measures, including water barriers, vary considerably based on risk exposure and recent flood experiences. Nevertheless, the estimates presented by Brody et al. (2017) and Botzen et al. (2019)

respectively provide lower (households that vary in exposure to flood risk) and upper (households in flood-prone areas which recently experienced floods) bounds of adoption of 2.6 to 32 percent. The studies that surveyed German households validate that range of adoption: Bubeck et al. (2013) and Kreibich et al. (2005) present estimates within that bound, while Grothmann and Reusswig (2006)'s adoption estimate is higher but comparable to Botzen et al. (2019)'s figure post-Hurricane Sandy.

4. Cost Analysis

4.1. Cost Overview

This Program was originally launched in 2012, and was developed primarily based on volunteer-led initiatives to establish initial standards and to create a website and a certification process. Since DHS actually did not run or finance this Program, there are no direct research and development or program costs to DHS or FEMA. The Program has been administered by the Corps of Engineers in cooperation with ASFPM and FM Approvals.

The limited investment by DHS in this program was through the coordination of various working groups and stakeholders from the community to identify the potential categories of products that would need new standards and to ensure that these products provide consumers the level of flood protection that the product manufacturers advertise.

The costs pertaining to this program that we have included in the analysis are:

1. Research and development costs by firms producing the floodproofing products. We assume that these are factored into the selling price of the products.
2. Program implementation costs (internal coordination and testing/certification costs). These are incurred by the three partner organizations that implement this Program. The following expenditures have been obtained from these entities.
    - Internal coordination costs: 40 hours of coordination for each manufacturer. Assuming an hourly rate of $50, $2,000 is needed to inform the manufacturer applicant about the entire auditing, testing, and certification program.
    - Program outreach: This refers to program promotion, conference attendance, website maintenance and updates, and production of marketing materials. While it was budgeted for $20,000 per year, the actual cost has been only a couple of

thousand dollars per year for several years so far (primarily focusing on website [https://nationalfloodbarrier.org/] maintenance and updates).

- All water-related testing is conducted in the Corps' Research and Development Center laboratory in Vicksburg, Mississippi. The costliest tests are those for temporary and semi-temporary barriers, which are estimated at about $65,000. This cost is paid entirely by the manufacturer.
- Material-related testing is conducted by FM Approvals. The cost per test is about $55,000 (again, paid entirely by the manufacturer). This cost also includes the cost of the initial manufacturing facility audit conducted by FM Approvals to ensure that the facility has the proper quality guidelines in place, so that the manufacturer has the capability to produce the product identical to the one tested (DHS, 2019).
- The cost of the testing equipment is around $75,000 to $125,000. It is assumed that no major replacement or upgrade of the testing equipment is needed within the 10-year analysis period. In addition, any maintenance and repair costs are assumed to be factored into the testing fees over time.

In summary, 13 products have been certified under the Program (ASFPM, 2019). These incurred the following total program-related costs:

- Internal coordination costs: $2,000x13=$26,000
- Program outreach: $3,000
- Water-related tests: $65,000x13=$845,000
- Material-related tests: $55,000x13=$715,000
- Testing equipment costs: $100,000

3. Product costs. This pertains to the price per unit of the various products developed under this Program. These data have been obtained from the product vendors and are presented in Table 2. The cost data include both product costs and installation costs. On average, installation costs are 30 to 50 percent of the product price. Moreover, we also assume that the storage costs of some of the temporary floodproofing products when not in use is near zero.

4.2. Cost Estimation

Program-related costs are presented in Table 1.

Table 1. Costs for Development and Implementation of Floodproofing Products Standards and Certification Program

Cost Category	Start	End	Amount	2017 Dollars	Source
Pre-project costs					
Project costs DHS (S&T/FEMA)					
Project costs (other entities)			129,000	125,932	ASFPM
Project costs (manufacturer, non-production)[a]			1,560,000	1,522,900	ASFPM
Project costs (contractor cost share)					
Oversight cost at DHS					
Transition development cost					
Implementation start up cost					
Implementation cost (User)					
Implementation cost (DHS)					
Implementation cost (Other users)					
TOTAL COST			$1,689,000	$1,648,832	

[a] These refer to the water-related testing and material-related testing costs of the certification program that were paid by the manufacturers of the tested products.

Initial cost estimates of the certified floodproofing products were obtained by contacting four companies, which produce nine of the 13 products.[8]

[8] Another producer, Taiwan-based Dai Chen, has three watertight gate products being certified under the program. However, an NDA form needs to be filled out in order to obtain pricing information of these products. We will not be pursuing this company for this study

Table 2. Product and Installation Costs of the Certified Floodproofing Products (per unit)

Product	Product Cost	Unit	Installation Cost
Perimeter Barriers			
Tiger Dam Perimeter Flood Barrier	$57	per linear foot	Accessory costs related to installation are about 30% of the product price
Tiger Dam 42-inch Flood Control	$80	per linear foot	Same as above
Aqua Fence Model V1200	$325	per linear foot	Training for self-installation included in price
Opening Protections/Barriers			
Presray FastLog Standard/Heavy Duty	$3,500 - 4,000	6' wide, 4' tall	$1,750 - 2,000
Presray Floodgate	$12,500 - 14,500	6' wide, 4' tall	$6,250 - 7,250
Presray Adjustable Flood Protection Door Barrier	$3,800	6' wide, preset height	$1,900
Presray Aluminum Panel	$ 9,500 - 11,500	6' wide, 4' tall	$4,750 - 5,750
PS Flood Plank Doors	$7,000	15' wide, 5' tall	$3,500
PS Single/Double Pedestrian Doors	$14,000	6' x 3' door	$7,000

We calculated an average cost of about $167 per linear foot for perimeter barriers based on the cost information for the Tiger Dam and Aqua Fence products (the accessory costs related to installation of the Tiger Dam products are included). This is lower than the average cost of $246 per linear foot of flood barriers (averaging $375 for metal and $117 for wooden shields) currently available in the market (AECOM, 2012; Aerts et al., 2014). The lower average cost we calculated is primarily due to the low cost of the Tiger Dam products. These products are elongated flexible tubes that can be stacked and joined to form water barriers and thus have a much lower unit cost compared to wooden or metal shields.

For the certified products used for opening protections and barriers, the total cost including installation ranges from $5,625 to $21,000. The average cost per product is around $13,000.

If we assume that each residential building for which dry floodproofing is an effective protection measure requires on average 40 linear feet of perimeter barriers, the total cost would amount to about $6,700 for each building. For commercial buildings, if we assume that on average 100 linear feet of perimeter protection and one opening protection product are needed, the total cost would amount to about $30,000 per building.

5. Benefit Analysis

5.1. Overview

This Program can potentially yield three benefits:

1. New products that can reduce more property damage than existing products. This applies to the current set of users of floodproofing products. The Flood Apex standard calls for the development of dry floodproofing products that can repel floodwaters of up to 4 feet and keep the building structures dry. The estimation here would involve comparing the reduction of flood damage by these new certified products with the average flood-height protection of products already in use (or purchased and on standby). The data needed for this estimation would include the average flood-height protection of existing products and the average annual estimates of the difference in flood damages between the current average height and the 4-foot standard promoted by the Flood Apex Program. The latter can be inferred from the literature or through the use of combination of flood maps and probability distributions of flood occurrence at various heights.
2. Wider adoption of floodproofing products that can reduce more damage. This applies to new users of floodproofing products attracted by the products' enhanced ability to reduce damage. Wider adoption of the new dry floodproofing products is more difficult to estimate because the lack of data on the relationship between product improvements and adoption rates. The research team contacted the organizations involved in product testing and certification, as well as manufacturers of these products. This type of information is not likely to have been developed by the former group, and one needs to consider the potential bias of the latter group in the promotion and marketing of their products. An alternative is to base the estimation on a range of potential increased adoption levels informed by anecdotal and other limited data.
3. Potentially more cost-effective floodproofing products. This applies to new users of floodproofing products attracted by the potentially lower cost of these products relative to those already in the market. The price of the various floodproofing products under the Flood Apex Program can be compared with similar products. If the price of the former is lower than the latter, then there are cost-savings which can

be added to the benefits side of the ledger. However, this can be complicated when the new products are compared to products that can only prevent water intrusion of heights lower than 4 feet.

A synthesis of the literature on similar dry floodproofing products currently in use is presented in Appendix Table A-2 in terms of costs and loss reduction potentials.

5.2. *Methodology*

The social cost of floods. Estimating the social cost of floods is a first step in quantifying the benefits of floodproofing. Essentially, the benefits of this mitigation tactic are the societal costs prevented. These costs potentially come from several sources of loss caused by flooding in general, though with varying relevance to the case in point. For example, death and injury is not likely to be a major factor here, because these floodproofing products offer protection of only up to 4 feet and require adequate warning time to actively deploy, and thus are of limited use against flash floods, the major source of deaths and injury. Their major benefit comes from avoiding property damage. They protect much less so against business interruption, since, again, flood heights of 4 feet or less typically cause only limited cessation or reduction of business activity. Household activity is usually not considered in formal economic accounts and is difficult to measure. In this case, it is more likely to pertain to considerations of relocation costs and inconvenience associated with workarounds or delays in undertaking household activities (see, e.g., Rose, 2004; Rose and Oladosu, 2008).

According to our DHS project contact, David Alexander, two major sources of information especially pertinent to estimating the benefits of flood hazard mitigation are:

1. The Flood Risk Assessment and Risk Reduction Plan developed by Charlotte-Mecklenburg Storm Water Services is used to assess the flood risk for each property in the county, identify effective flood hazard mitigation techniques, and develop Flood Mitigation Priority Scores in order to prioritize individual properties (or property groups) for flood mitigation efforts (AECOM, 2012). Appendix F, Benefit-Cost Assumptions, in the AECOM (2012) report provides unit cost information on dry floodproofing techniques.
2. The Benefit-Cost Analysis (BCA) Tool developed by FEMA (2009) is used as a standardized method to perform quantitative evaluation of the cost-effectiveness of

disaster mitigation projects submitted under FEMA's Hazard Mitigation Assistance grant programs. Data required for using the tool include project cost estimates (e.g., materials, labor, contractor and management costs), damage history, property information (e.g., location, building/structure type, size, occupancy, etc.), and engineering and design information (FEMA, 2009). Although it would not be possible for us to conduct BCAs for each individual property or mitigation project for this study, we will utilize some standard values and assumptions in the tool, including benefit estimates.

Benefit estimation for temporary flood barriers. Our investigation has identified two prime methods for estimating the benefits of floodproofing. The first, which might be termed "direct estimation," involves using data that combines the following considerations:

- flood height
- flood damage
- flood protection measures in place

If data were available for all three of these, we could implement the following set of calculations for an average building in a given building class:

1. Determine average flood damages at water heights of 4 or more feet
2. Determine the current average level of dry floodproofing protection in terms of the number of feet
3. Determine the average flood damages at current protection levels (this is simply flood damages in a recent year or average of a series of years)
4. Subtract result #3 from result #1 to determine the improvement that can be brought about by implementing new floodproofing products (assuming they provide high quality protection at an average of 4 feet).

The next step in the calculation is to determine the number of buildings to which the floodproofing products are applicable and would be put in place. This, however, is more of an issue of technology adoption to be discussed below.

The problem here is the availability of data. The Federal Insurance & Mitigation Administration National Flood Insurance Program (FIMA NFIP) Redacted Claims Dataset includes amounts paid for building and content damages for properties damaged by flood. The dataset does not include building addresses, but specifies the census tract and type of flood zone the properties are located in. Flood depth can be interpolated for major flooding events, such as Hurricane Sandy or Hurricane Harvey. The current average level of protection for specific buildings is not likely to be known, however. Note that the estimation of deaths and injuries is not relevant to this floodproofing project because flood protection of only 4 feet is not likely to have any effect on this damage category. Direct and indirect economic losses from flooding, including content damage, relocation expenses, and forgone income and output, can be inferred from HAZUS-MH data, which essentially combines capital-output ratios and recovery time for various building types and damage levels.[9]

The second approach is “benefits transfer,” which refers to the broad category of techniques using the concept of an analogy. That is, one adapts findings from another location, economic sector, and/or time period for the case in point. The technique ranges from simple adaptation, with some crude adjustments for size (population, economic activity) and time (economic growth or technological change), to the more sophisticated variant of what is known as benefit function transfer, where the analyst performs statistical analyses for one case or cases and applies the function to the case in point, filling in the values of explanatory variables (Boutwell and Westram, 2013; Johnston et al., 2015). Data are not available for us to perform a benefit function transfer, however, for this application.

Many researchers have estimated the benefits of various protective measures, but not specifically for the FRG Flood Apex products. Moreover, many of these estimates are performed for non-applicable areas (such as coastal areas) or non-applicable countries (foreign countries with much different building stocks). The most promising of such results relates to the work of ICPR (2002), Kreibich et al. (2005), and DEFRA (2008), which estimate the efficacy of different dry floodproofing measures, including water barriers similar to the FGR Flood Apex products. The most recent literature on flood mitigation strategies (Aerts et al. [2014], Botzen et al. [2017], and de Ruig et al. [2019]) uses those three studies to estimate the efficacy of dry floodproofing.

Another set of applicable findings to which we can apply benefit transfer are the results of the application of the FEMA hazard loss estimation tool, HAZUS (FEMA, 2013a). For example, the HAZUS user manual provides data on percent building damage by flood depth for various categories of buildings. Note that these estimates are based on well-vetted flood damage

[9] In addition, some adjustments for property damage between buildings and contents needs to be made.

functions applied to extensive building inventories for the U.S. as a whole. However, a substantial amount of additional information is needed to apply the depth-damage functions to estimate flood damages in dollar values. Below, we briefly summarize the necessary data and analysis steps:

1. The general building stock inventory data in terms of the total number of buildings and their total replacement values within a given region can be obtained from the HAZUS-MH software.
2. Flood risk maps (such as for 10-, 25-, 50-, 100-, and 500-year flood) are needed to show the expected water surface elevations for flood events of different recurrence intervals in different floodplain areas.
3. By overlapping the flood risk maps and the elevation map of individual buildings, probability distributions of flood depths for each census block within the floodplains can be developed.
4. The potential building and content losses in each floodplain can be estimated by combining the information on flood depth distributions, the depth-damage functions (provided by HAZUS),[10] and the displacement value of buildings at risk.

Estimation of average annual losses from flood events. The National Oceanic and Atmospheric Administration (NOAA)'s Storm Events Database was used to estimate property damage from flood events over the past 15 years. Annual property damage related to floods, flash floods, debris flow, and coastal flood events from 2004 to 2018 were considered. Property damage estimates were also assessed from claims paid by the National Flood Insurance Program (NFIP) each year, available from the Federal Insurance & Mitigation Administration NFIP Redacted Claims Dataset (FEMA, 2019).

Flood events have caused on average $9.1 billion (2017 dollars) in property damage each year from 2004 to 2018. Over that period, damages have ranged from approximately $1.5 billion in 2009 to nearly $65 billion in 2017. The amount paid in NFIP claims on buildings and content over that 15-year period averaged $4.2 billion (in 2017 dollars) each year, of which $3.78 billion are for residential claims and $0.402 billion are for commercial claims (including both building and content losses). Over the same period, the average annual number of residential claims

[10] Note that similar tables are available for commercial buildings as well.

was 75,624. For commercial claims, it was 4,796. The discrepancy between flood damage estimates and NFIP claims paid is unsurprising, as not all flood-prone structures are NFIP-insured. Based on the NFIP claims data, the average claim was $49,989 per residential building and $83,967 per commercial building.

NOAA's Storm Events Database is based on open sources, including reports from print and broadcast media, law enforcement, and the park and forest services. Therefore, the database's estimates of property damage and casualties are prone to measurement error. Nevertheless, the database provides a rough estimate of damage and casualties related to floods.

5.3 Technology Adoption

The benefits of dry floodproofing are highly dependent on the extent to which the new technology and products are adopted. The fact that adoption of dry floodproofing may help reduce premiums of NFIP flood insurance for a non-residential building provides some solid basis for this estimation. For example, we can use the number of flood damage claims in recent years as a starting point. However, adoption is likely to extend beyond those structures damaged to a broader set of owners of structures who are concerned about flood damage. We will explore several options, some noted below, and also consider using a reasonable range of upper- and lower-bound adoption scenarios.

Based on conversations with the organizations implementing this program, we identify a few factors that may drive market penetration:

- The current Program is working towards getting the FM2510 Standard adopted into ASCE-24 on Flood Resistant Design Standards (ASCE, 2019), and ultimately into the International Building Code (IBC). This will promote the market adoption of these new certified products.
- The Corps of Engineers is the largest purchaser of flood barriers and floodproofing products in the U.S. Since the Corps of Engineers is one of the partners of this Program, it is likely that it would reference the ASCE-24 standards and use them as the basis for its contracting choices of specific products.
- The National Flood Insurance Program (NFIP) requires property owners to use certified products for retrofitting in order to receive reimbursements. Also, for commercial

buildings, dry floodproofing is a qualified compliance technique for local regulations or building codes that the NFIP requires (FEMA, 2013b).

5.4. Benefits Calculation

Table 3 presents the main assumptions used in the base case benefit calculations and the results.

First, based on the information we gathered from the literature (Appendix Table A-2), we assume that the adoption of dry floodproofing products, especially the perimeter and opening barriers and protection products certified by the Program so far, can help reduce potential property losses by 25 percent.[11] Second, we assume that the baseline dry floodproofing adoption rate is 8 percent in the base case. This is towards the lower-end of the baseline adoption range (from 2.6 to 32 percent) we found in the literature and discussed in section 3. This is because the lower-end estimate was based on a survey across property owners exposed to different levels of flood risks, while the upper-end estimate was based on a survey for households in high-risk flood-prone areas that had just recently experienced a major flood event. Third, we assume that the Program will help increase the baseline adoption rate by 20 percent (from 8 to 9.6 percent). We then apply the 1.6 percent increased adoption rate to the average annual numbers of both residential and commercial claims based on NFIP data to calculate the total additional adoption of dry floodproofing measures. In this step, we also consider that insured losses only represent about 46 percent of the total property damage from flood events (NOAA, 2019).

In the rest of Table 3, we calculated both the benefits (potential avoided property losses) and the associated adoption cost of dry floodproofing products for both residential and commercial buildings. The average annual benefits and the discounted benefits over the future 10-year period are summarized in the next section.

[11] Some of the studies reviewed in Appendix Table B indicate higher loss reduction potentials. However, most of those studies focus on the adoption of a combination of various types of dry floodproofing products and techniques. Given that we only focus on two types of dry floodproofing products that are currently being certified by the Program, we have adopted the lower-end estimate of loss reduction potential in the literature for the base case of this study in order to be conservative.

Table 3. Base Case Analysis of the Benefits of the Floodproofing Products Standards and Certification Program

Variable	Base Case
% Property Loss Reduction by Using Dry Floodproofing	25%
Percent of Properties Insured	46%
Baseline Dry Floodproofing Adoption Rate	8%
Increased Adoption Rate	1.60%
Total # of Additional Adoptions for Residential Buildings	2,420
Total # of Additional Adoptions for Commercial Buildings	167
Potential Annual Avoided Losses (Res) ($)	30,242,705
Potential Annual Avoided Losses (Com) ($)	3,501,798
Per Building Cost of Dry Floodproofing (Res) ($)	6,706
Per Building Cost of Dry Floodproofing (Com) ($)	29,903
Cost of Dry Floodproofing (Res) ($)	16,228,951
Cost of Dry Floodproofing (Com) ($)	4,988,368
Total Cost of Dry Floodproofing (Res + Com) ($)	21,217,319
Total Program Costs ($)	1,648,832
Discount Rate	3%
Total Annual Benefits (Potential Annual Avoided Losses – Res + Com) (2017$)	3,744,503
Ten-year Discounted Benefits (2017$)	295,349,747
Ten Year Net Benefits (Benefits - Program Cost - Floodproofing Cost) (2017$)	272,483,596
Benefit-Cost Ratio for Program	**179.1**
ROI for Program	**17,813**
Benefit-Cost Ratio for Implementation	**12.9**
ROI for Implementation	**1,192**

6. Net Benefits, Benefit-Cost Ratio, and Return on Investment

Table 3 shows that the total annual benefits of the increased adoption of the Program's certified dry floodproofing products are about $33.7 million. The 10-year discounted benefits are about $295.35 million. After we subtract the Program costs and the installed costs of the dry floodproofing certified products, the NPV of the net benefits is estimated at $272.48 million in the base case analysis. Given the $1.65 million Program costs, the benefit-to-cost ratio for the Program is 179.1, and the return on investment (ROI) for the Program is 17,813 percent. In addition, we also calculated the BCR and ROI for the implementation of the dry floodproofing techniques. The BCR for implementation is 12.9, and its ROI is 1,192 percent.

7. Sensitivity and Uncertainty Analysis

Break-even analysis. One way to evaluate the cost-effectiveness of the Floodproofing Products Standards and Certification Program is to determine the lowest adoption rate of the dry floodproofing products stemming from this Program for which the associated benefits from property loss avoidance can exceed the Program costs. The calculation indicates that the Program only needs to increase the baseline adoption rate from 8 to 8.009 percent to reach the break-even point, holding all other variables constant at their base case values.

Sensitivity analysis. The estimated net benefits associated with the National Floodproofing Products Standards and Certification Program are sensitive to some of the assumed parameters. There are eight uncertain parameters in the net benefits calculation. Table 4 presents the range of values for each of the parameters adopted in the sensitivity analysis. The first two parameters relate to the increased adoptions of dry floodproofing products because of the Program, which is estimated based on a combination of assumptions on the baseline adoption rate of these products and the potential increased adoption measured as a percent of the baseline adoption rate. The next two parameters are the average per building cost of dry floodproofing for residential and commercial buildings, respectively. The major parameters used to estimate the benefits of the adoption of dry floodproofing include the average annual property damages from flood events per building for both residential and commercial buildings and the percent property loss reduction by adopting dry floodproofing. The final parameter we included in the sensitivity analysis is the discount rate.

Table 4. Ranges of Variable Values for the Floodproofing Products Standards and Certification Program Analysis

Input Variables	Low	Base	High
Baseline Dry floodproofing Adoption Rate	2.6%	8%	32%
Increased Adoption (as a Percent of the Baseline Adoption Rate)	10%	20%	30%
Cost of Dry Floodproofing Per Building (Residential)	5,365	6,706	8,048
Cost of Dry Floodproofing Per Building (Commercial)	23,923	29,903	35,884
Annual Losses from Flood Events Per Building (Residential)	39,991	49,989	59,986
Annual Losses from Flood Events Per Building (Commercial)	67,174	83,967	100,761
% Property Loss Reduction by Using Dry Floodproofing	20%	25%	30%
Discount Rate	0%	3%	7%

Figure 1 presents a “tornado diagram,” which shows how changes in the underlying input parameters affect the net benefit estimate of the Floodproofing Products Standards and Certification Program. In the tornado diagram, the length of the bar for each input variable represents the range of the 10-year net benefits that results from using the low and high values of this variable while holding the other variables at their base values. The most important parameters are those with the longest bars in the diagram. The sensitivity analysis indicates that the estimates of the 10-year net benefits are most sensitive to assumptions about the baseline dry floodproofing adoption rate and the increase in adoption as a percent of the baseline adoption rate. Other important variables include annual losses from flood events per residential building and the percent of property losses that can be reduced by adopting dry floodproofing.

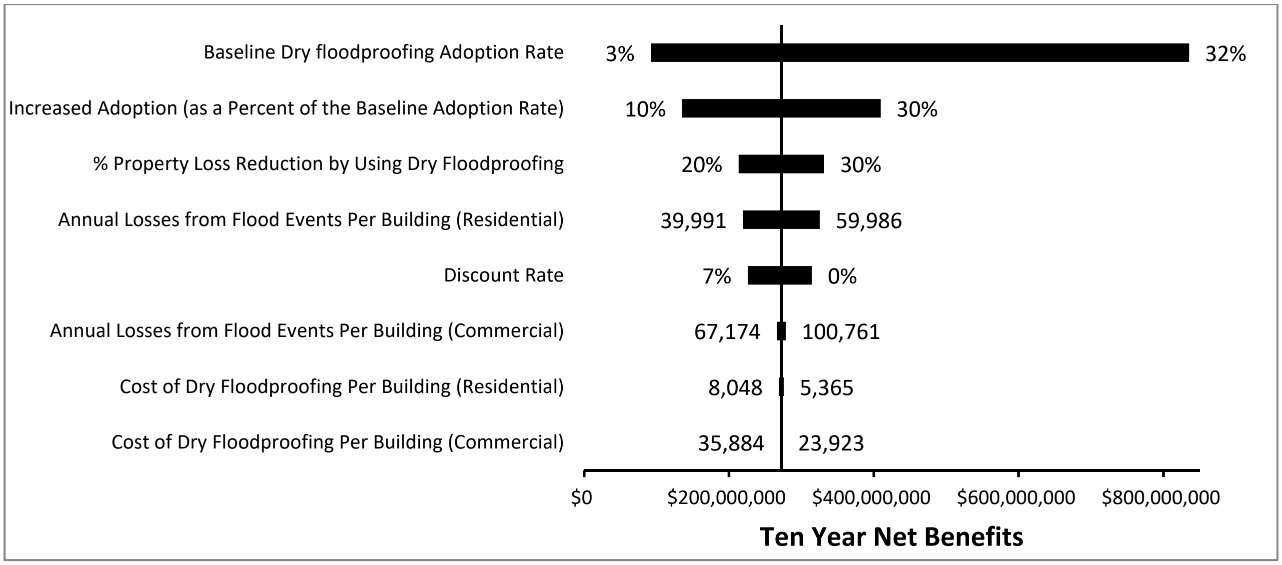

Figure 1. Tornado diagram for 10-year net benefits of the Floodproofing Products Standards and Certification Program

Uncertainty analysis. To explore the uncertainty associated with the estimates of the 10-year net benefits, we conducted a Monte Carlo simulation. We assume triangular probability distributions for all variables listed in Table 4, using the low and high values as the minimum and the maximum, respectively, of the triangular distribution, and the base case value as the mode. Next, 10,000 simulations were run to obtain the distribution of the 10-year net benefits as presented in Figure 2. The 5th, 50th, and 95th percentiles, as well as the mean and median of the distribution, are presented in Table 5. The simulation estimated a mean net benefits of $447.7 million, with a 5th percentile of $154.1 million and a 95th percentile of $861.1 million.

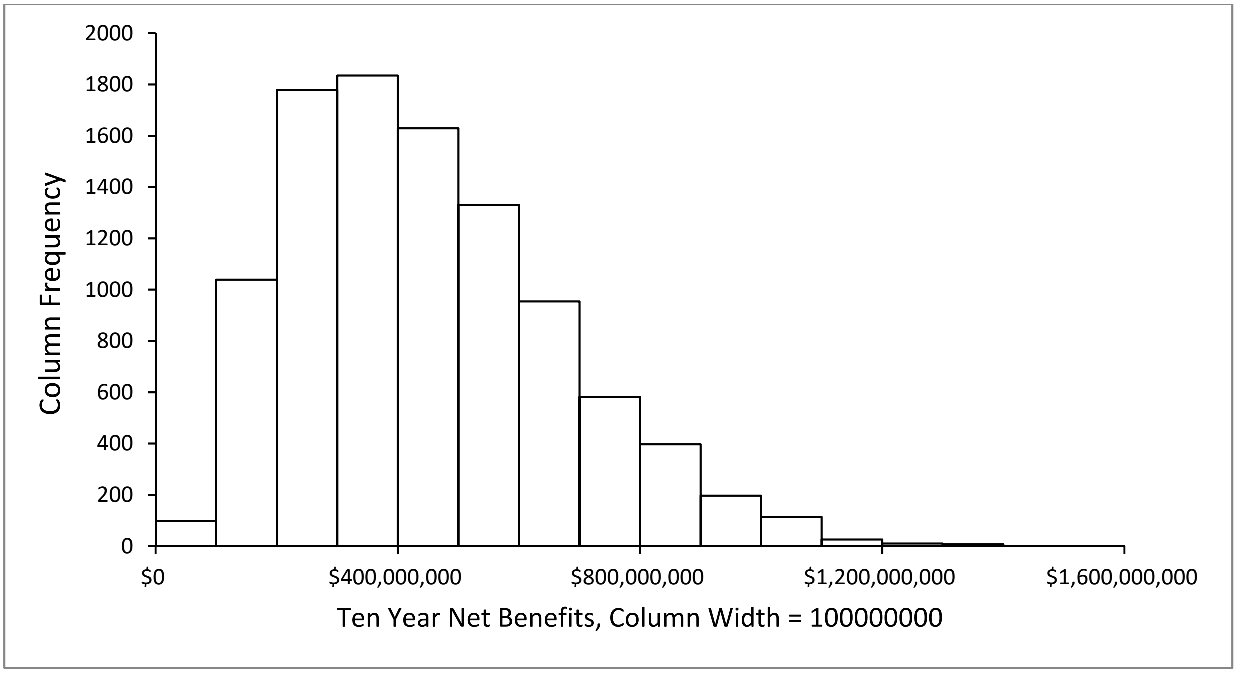

Figure 2. Distribution of 10-year net benefits of the Floodproofing Products Standards and Certification Program

Table 5. Statistics of the Net Benefits Distribution

Mean	$447,746,778
St. Dev.	$217,249,732
5th Percentile	$154,086,063
25th Percentile	$279,897,700
Median	$414,637,414
75th Percentile	$580,908,884
95th Percentile	$861,078,222

8. Assumptions and Limitations

Several assumptions are adopted in this study to evaluate the net benefits of the Floodproofing Products Standards and Certification Program. One of the major assumptions is the increased adoption of the dry floodproofing products as a result of this Program. Since we were not able to obtain a direct estimate on this parameter from the organizations managing this

Program or from the manufacturers of the certified products, we have estimated the increased adoption rate as a product of the baseline adoption rate of similar products and the potential increased adoption measured as a percentage of the baseline adoption rate. We found a wide range of estimates on the baseline adoption rate in the literature and adopted a base case rate towards the lower-end of these estimates as a weighted average adoption rate of property owners that are exposed to different levels of flood risks. We further assumed that the Program will help increase the baseline adoption rate by 20 percent (from 8 to 9.6 percent).

The other major assumption is with respect to the flood-related property damages that can be potentially avoided from the increased adoption of the dry floodproofing products. An extensive literature review was conducted, but most of the studies reviewed estimate the loss reduction potentials from the adoption of a combination of various dry floodproofing products and techniques. Since there were only two types of dry floodproofing products being certified by the Program when this study is conducted, we conservatively adopted the lower-end estimate of loss reduction potential in the literature for the base case.

Even with the above two major assumptions on the conservative side, the sensitivity analysis indicates that the Floodproofing Products Standards and Certification Program has the potential to provide substantial net benefits over a 10-year period.

9. Additional Research

To improve the evaluation of the net benefits from the Program, it would be valuable to collect data on the increased adoption of the certified floodproofing products and the loss reduction potentials of these specific products. It would be best if such information can be gathered from the companies that produce and sell these dry floodproofing products. For example, interviews can be conducted with these companies to gather estimates on the increased sale of these products after they passed the FM 2510 standard tests and received the FM Approved mark. With further assistance from these companies, a survey can be conducted among their customers after a major flood event to evaluate the extent to which losses have been reduced because of the implementation of these floodproofing measures.

10. References

AECOM. (2012). *Flood Risk Assessment and Risk Reduction Plan*. Report to Charlotte-Mecklenburg Storm Water Services. Available at: https://charlottenc.gov/StormWater/Flooding/Documents/Flood_RARR_Plan-Final.pdf.

Aerts, J. C., Botzen, W. W., Emanuel, K., Lin, N., De Moel, H., & Michel-Kerjan, E. O. (2014). Evaluating flood resilience strategies for coastal megacities. *Science*, *344*(6183), 473-475. https://science.sciencemag.org/content/344/6183/473.

American Society of Civil Engineers (ASCE). (2019). *ASCE-24 Standards*. Available at: https://ascelibrary.org/doi/book/10.1061/asce24.

Association of State Floodplain Managers (ASFPM). (2016). *National Flood Barrier Test Program*. Available at: https://nationalfloodbarrier.org/docs/NationalFloodBarrierTestProgramDocumentDraft.pdf.

Association of State Floodplain Managers (ASFPM). (2019). *National Flood Barrier Testing & Certification Program*: *Lists of Tested and Certified Products*. Available at: https://nationalfloodbarrier.org/.

Botzen, W. J., Kunreuther, H., Czajkowski, J., & de Moel, H. (2019). Adoption of Individual Flood Damage Mitigation Measures in New York City: An Extension of Protection Motivation Theory. *Risk Analysis*. https://onlinelibrary.wiley.com/doi/full/10.1111/risa.13318.

Botzen, W. W., Monteiro, É., Estrada, F., Pesaro, G., & Menoni, S. (2017). Economic Assessment of Mitigating Damage of Flood Events: Cost–Benefit Analysis of Flood-Proofing Commercial Buildings in Umbria, Italy. *The Geneva Papers on Risk and Insurance-Issues and Practice, 42(4)*, 585-608. https://link.springer.com/article/10.1057/s41288-017-0065-0.

Boutwell, J., & Westra, J. (2013). Benefit transfer: A review of methodologies and challenges. *Resources*, *2*(4), 517-527. https://pdfs.semanticscholar.org/4f65/d3b4227fbcb2bc20a1a057dbd0015b6d4f18.pdf

Brody, S. D., Lee, Y., & Highfield, W. E. (2017). Household adjustment to flood risk: a survey of coastal residents in Texas and Florida, United States. *Disasters*, *41*(3), 566-586. https://onlinelibrary.wiley.com/doi/full/10.1111/disa.12216.

Bubeck, P., Botzen, W. J., Kreibich, H., & Aerts, J. C. (2013). Detailed insights into the influence of flood-coping appraisals on mitigation behaviour. *Global Environmental Change*, *23*(5), 1327-1338. https://www.sciencedirect.com/science/article/abs/pii/S0959378013000836?via%3Dihub

Congressional Budget Office (CBO). (2019). *Expected Costs of Damage from Hurricane Winds and Storm-Related Flooding*. Available at: https://www.cbo.gov/publication/55019.

Cutter, S. (2016). "The Landscape of Disaster Resilience Indicators in the USA," *Natural Hazards* 80(2): 741-758.

DEFRA. (2008). Developing the evidence base for flood resistance and resilience: summary report. R&D Technical report FD2607/TR1.Environment Agency and the Department for Environment Food and Rural Affairs (DEFRA), London. http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=14738.

Department of Homeland Security (DHS). (2019). *National Resilience Standards for Flood Proofing Products Project*. DHS Science and Technology Directorate. https://www.dhs.gov/publication/st-national-resilience-standards-flood-proofing-products-project-fact-sheet.

de Ruig, L. T., Haer, T., de Moel, H., Botzen, W. W., & Aerts, J. C. (2019). A micro-scale cost-benefit analysis of building-level flood risk adaptation measures in Los Angeles. *Water Resources and Economics*, 100147. https://doi.org/10.1016/j.wre.2019.100147.

FEMA. (2009). *Final BCA Reference Guide*. Retrieved from https://www.fema.gov/media-library/assets/documents/18870.

FEMA. (2013a). Flood Model Technical Manual (Hazus 2.1). https://www.fema.gov/media-library-data/20130726-1820-25045-8292/hzmh2_1_fl_tm.pdf.

FEMA. (2013b). Floodproofing Non-Residential Buildings. Available at: https://www.wbdg.org/FFC/DHS/femap936.pdf.

FEMA. (2019). FEMA NFIP Redacted Claims Data Set [Data file]. Retrieved from https://www.fema.gov/media-library/assets/documents/180374.

FM Approvals. (2019). *Our Mission*. Available at: https://www.fmapprovals.com/about-fm-approvals/our-mission.

Grothmann, T., & Reusswig, F. (2006). People at risk of flooding: why some residents take precautionary action while others do not. *Natural hazards*, *38*(1-2), 101-120. https://doi-org.libproxy2.usc.edu/10.1007/s11069-005-8604-6

ICPR. (2002). Non-structural flood plain management: measures and their effectiveness. International Commission for the Protection of the Rhine (ICPR). https://www.iksr.org/fileadmin/user_upload/Dokumente_en/rz_iksr_engl.pdf.

Johnston, R. J., Rolfe, J., Rosenberger, R. S., & Brouwer, R. (2015). Introduction to benefit transfer methods. In *Benefit Transfer of Environmental and Resource Values* (pp. 19-59). Springer, Dordrecht. https://link.springer.com/chapter/10.1007/978-94-017-9930-0_2

Kreibich, H., Christenberger, S., & Schwarze, R. (2012). Corrigendum to" Economic motivation of households to undertake private precautionary measures against floods" published in Nat. Hazards Earth Syst. Sci., 11, 309–321, 2011. *Natural Hazards and Earth System Sciences*, *12*(2), 391-392. https://www.nat-hazards-earth-syst-sci.net/12/391/2012/.

Kreibich, H., Christenberger, S., & Schwarze, R. (2011). Economic motivation of households to undertake private precautionary measures against floods. *Natural Hazards and Earth System Sciences*, *11*(2), 309-321. https://www.nat-hazards-earth-syst-sci.net/11/309/2011/.

Kreibich, H., Thieken, A. H., Petrow, T., Müller, M., & Merz, B. (2005). Flood loss reduction of private households due to building precautionary measures--lessons learned from the Elbe flood in August 2002. *Natural Hazards and Earth System* Sciences, 5(1), 117-126. https://www.nat-hazards-earth-syst-sci.net/5/117/2005/.

Lightbody, L. (2017). *Flooding Disaster Cost Billions in 2016*. PEW Article. Available at: https://www.pewtrusts.org/en/research-and-analysis/articles/2017/02/01/flooding-disasters-cost-billions-in-2016.

National Oceanic and Atmospheric Administration (NOAA). (2019). Storm Events Database [Data file]. Retrieved from https://www.ncdc.noaa.gov/stormevents/.

Nunez, C. (2019). *Floods, Explained*. National Geographic Reference. Available at: https://www.nationalgeographic.com/environment/natural-disasters/floods/.

Osberghaus, D. (2017). The effect of flood experience on household mitigation—Evidence from longitudinal and insurance data. *Global environmental change*, *43*, 126-136. https://doi.org/10.1016/j.gloenvcha.2017.02.003.

Poussin, J. K., Botzen, W. W., & Aerts, J. C. (2015). Effectiveness of flood damage mitigation measures: Empirical evidence from French flood disasters. *Global Environmental Change*, *31*, 74-84. https://www.sciencedirect.com/science/article/pii/S0959378014002167.

Rose, A. (2004). “Economic Principles, Issues, and Research Priorities in Natural Hazard Loss Estimation,” in Y. Okuyama and S. Chang (eds.), *Modeling the Spatial Economic Impacts of Natural Hazards*, Heidelberg: Springer, pp.13-36.

Rose, A. (2017). “Economic Resilience to Terrorism and Natural Disasters,” in A. Abbas, M. Tambe and D. von Winterfeldt (eds.), *Improving Homeland Security Decisions*, New York: Cambridge University Press.

Rose, A. and G. Oladosu. (2008). “Regional Economic Impacts of Natural and Man-Made Hazards Disrupting Utility Lifeline Services to Households,” in H. Richardson, P. Gordon and J. Moore (eds.), *Economic Impacts of Hurricane Katrina,* Cheltenham, UK: Edward Elgar.

Appendix Table A-1. Literature Synthesis of Dry Floodproofing Adoption

Study	Location	Sample	Type of Products	Adoption Rate	Comments
Botzen et al. (2019)	New York City	1,035 homeowners who reside in a house with a ground floor in flood-prone areas of New York City.	Water-proofed walls Installed pump or drainage system Flood shields or sand bags	Before last flood (After) 20% (31%) 39% (46%) 25% (32%)	69% of respondents took at least one dry flood-proofing measure
Brody, Lee, & Highfield (2017)	Four communities in coastal Florida and Texas	342 households in 100-year floodplain, 500-year floodplain, and minimal flood hazard areas.	Adding a waterproof veneer to the exterior walls or sealing openings with shields or sandbags to prevent water from entering.	2.6%	
Bubeck et al. (2013)	Rhine, Germany	752 flood-prone households along the Rhine	Fixed or mobile flood barriers.	17%	
Grothmann & Reusswig (2006)	Cologne, Germany	157 residents of flood-prone homes.	Purchase of flood protection devices like protective barriers for windows and doors or pumps (devices)	38% of respondents had purchased flood protection devices	
Kreibich et al. (2005)	Saxony and Saxony-Anhalt, Germany	1,200 private households affected by the 2002 flood at the river Elbe.	Water barriers available	Before flood (After) 7% (27%)	

Osberghaus (2017)	Germany	7,400 German households.	Protection flap for cellar windows and doors (only households with cellar)	Before flood (After) 3% (4%)
			Backflow flap (only homeowners)	30% (36%)
			Water-repellent exterior plaster (only homeowners)	13% (15%)
			Water-repellent internal coating	3% (3%)

Appendix Table A-2. Literature Synthesis of Dry Floodproofing Products

Study	Location	Type of Products	Cost of Products	Damages Prevented: Estimates	Damages Prevented: BCRs	Comments
Aerts et al. (2014)	New York City and New Jersey	Cost estimates from FEMA (2009) for dry floodproofing houses up to a level of 3 feet: Sprayed-on cement (above grade) Waterproof membrane (above grade) Asphalt (two coats on foundation up to 2 ft below grade) Drainage line around perimeter of the house Plumbing check valve Sump and sump pump (with backup battery) Metal flood shield Wooden flood shield	 $16.80 / linear ft of wall covered $5.70 / linear ft of wall covered $12.00 / linear ft of wall covered $31 / linear ft $1,060 each $1,710 lump sum $375 / linear ft of shield surface $117 / linear ft of shield surface	75-87.5% decrease in flood damage for a combination of dry floodproofing techniques based on ICPR (2002), Kreibich et al. (2005), and DEFRA (2008).	BCRs of dry flood-proofing existing buildings in 1/100 flood zones up to 6-ft range from .37 - 3.93 depending on climate change scenario, estimated effectiveness, and discount rate.	Projected cost per building category for dry floodproofing up to 6 ft, scaled up for New York City construction costs: RES1: $16,726 RES2: $18,912 RES3A: $17,664 RES3B: $21,126
Botzen et al. (2017)	Umbria, Italy	Sealing walls, building drainage line, installing a sump pump, installing plumbing check valves, flood shields (up to a level of 3.9 ft)	Cost estimates from FEMA (2009): $10,890-23,894 depending on commercial building category Converted from EUR based exchange rate at date of article submission	Same as estimates from Aerts et al. (2014).	Baseline BCRs range from .5 to 3.7 depending on business type for floodproofing buildings up to a level of 3.9 feet of flood water	BCR also reported based on different flood probabilities. BCR also reported for floodproofing of up to 6 ft.
DEFRA (2008)	United Kingdom	Manually installed door guards and air brick covers, sump/pump and remedial works to seal water entry points.		47-53% reduction in the cost of damages	For residences in zones affected every 5/10/25/50/100 years: 10.6/5.8/2.6/1.3/0.3	

		Permanent floodproof external doors, automatic air bricks and external wall render / facing, sump/ pump and remedial works to seal water entry points.	Not specified	65-84% reduction in the cost of damages	8.4/4.3/1.8/0.9/0.2 Calculated on the basis of a typical individual UK property	
de Moel et al. (2014)	Rotterdam, Netherlands	Closing of openings (doors, windows), waterproofing the outside wall, installing back stop valves (up to a level of 3.3 ft)	Not specified	For 3.3-ft dry proofing: 61% total flood damage reduction under current climate conditions 89% flood damage reduction for residential buildings under current climate conditions	Not specified	Dry floodproofing all buildings has an effect about as large as elevating all buildings with 1.6–3.3ft. Dry floodproofing is particularly effective at low (<3.3 ft) inundation depths
de Ruig et al. (2019)	Los Angeles County (Naples and Venice Beach)	Not specified	Projected cost for dry floodproofing up to 6 ft, scaled up for Los Angeles construction costs: RES1: $14,211 RES2: $16,069 RES3A: $15,008 RES3B: $17,949	75% decrease in flood damage based on Aerts et al. (2014).	BCR > 1 in all scenarios for Naples and in all scenarios that account for some sea-level rise for Venice Beach	BCR not directly reported; only aggregate NPV by area included in supplementary materials
ICPR (2002)	Rhine, Europe	Waterproofing cellar Pumping water Shielding	Not specified	75-85% damage reduction 50-60% (only cellar); 60-70% (cellar and ground floor) 60-80% (if cellars are sealed, nearly 100%)	Not specified	Not specified
Kreibich et al. (2005)	Germany (Saxony	Water barriers		29% reduction in the mean damage ratio for	Not estimated	Building and contents damage ratios for

	and Saxony-Anhalt)	Stable building foundation or waterproof sealed cellar walls	Not estimated	buildings; no effect on preventing damage to contents. 24% reduction in the mean damage ratio for buildings; no effect on preventing damage to contents.		households who lived in buildings with and without flood adapted use were calculated based on surveys of residents of flood-affected areas.
Kreibich et al. (2011), Kreibich et al. (2012)	Germany (Saxony and Saxony-Anhalt)	Waterproof skin (bitumen sealing) Concrete tanked slab and waterproof interstices Mobile water barriers	$2,918-6,023/year $3,330-6,873/year $709-859/year (Converted from EUR)	Same as estimates from Kreibich et al. (2005)	For zones affected every 1/10/50 years: 7.93-33.92 / 0.79-3.39 / 0.16-0.68 6.95-29.72 / 0.70-2.97 / 0.14-0.59 56.19-61.14 / 5.62-6.11 / 1.12-1.22	BCRs for mobile water barriers vary based on discount rate used. BCRs for waterproof skin and waterproof concrete vary based on discount rate and whether only the cellar or both the cellar and the ground floor are affected.
Poussin et al. (2015)	France (Ardennes, Var, and the West Coast)	Anti-backflow valves Sandbags or water barriers	$1,113-2,435 $369-1,176 for wood or metal barriers (Converted from EUR)	65% (-$11,945) to building damage and -38% (-$4,067) to building contents Not statistically significant Structural damage rises sharply after 3.3ft inundation depth, but remains 15% lower as the water-resistant material will still result in less damage.	Not estimated	Based on regression analysis of survey on flood damage experienced and household flood preparedness

Benefit-Cost Analysis of Low-Cost Flood Inundation Sensors[12]

Analysts: Adam Rose, Dan Wei, Juan Machado, and Kyle Spencer

October 2019

1. Summary

The purpose of the Flood Apex project is to develop and test low-cost flood inundation sensors that can readily be deployed in a wireless or internet of things (IoT) network. The use of such sensors can improve the prediction accuracy and lengthen the lead time of flood warning systems. DHS and the Small Business Administration have provided funding for the development and testing of this new product, which has progressed through three phases; the current phase evaluates its commercial viability. Expectations are optimistic given the demonstrated low cost of producing the sensors. The intent is that the availability of these products will induce potential users to adopt them. This pertains both to users who are already purchasing flood sensors of lower quality/effectiveness and those who previously had not adopted such technology but are attracted by the relatively much lower cost of the new products.

Research and development costs are relatively minor compared to the market potential of these new products. The production costs of this new technology are only a fraction of those of existing sensors, and operating costs are modest. Ancillary products that enhance the operation of the sensors, such as cameras, are relatively inexpensive as well, with a wide variety of options available because of the modularity of the overall sensor system. Benefits depend on such factors as the ability of improved lead times of warnings to reduce property damage and deaths from floods, as well as the extent of adoption of the new sensors.

Our preliminary analysis indicates a benefit-cost ratio (BCR) of 2.7 and a rate of return on investment of 174.8 percent. However, our results are based on a number of simplifying assumptions. Hence, we have undertaken a sensitivity analysis.

[12] Adam Rose, Dan Wei and Juan Machado are with the Center for Risk and Economic Analysis of Terrorism Events (CREATE); Kyle Spencer is with the City of Norfolk, Virginia Planning Department. The authors acknowledge the valuable input by Jeff Booth, David Alexander, Ian Helmuth, Jennifer Foley, and Scott Farrow. We also appreciate the research assistance of Konstantinos Papaefthymiou, Peter Eyre, and Shannon Prier. The authors are solely responsible for any errors or omissions.

2. Description of the Project

Substantial damages have been caused by floods in the U.S., resulting in an average of 80 fatalities per year and amounting to an average annual economic loss of nearly $8 billion over the past three decades (Lightbody, 2017; DHS S&T, 2018). Despite increased investment in flood control and warning systems, the combination of increasing extreme storm events, changes in land use, and a build-up of the number of assets at risk has resulted in an increasing trend of economic losses caused by floods. Based on a recent study by the Congressional Budget Office (CBO, 2019), the expected damages from storm-related flooding in the U.S. could reach as high as $20 billion annually in the near future, nearly 75 percent of which would occur in the residential sector. The demand for inexpensive and reliable warning systems has thus increased in recent years with this anticipated increase in the number and severity of flooding disasters.

The main purpose of developing and testing low-cost flood inundations sensors is to promote the adoption of these products, primarily by local governments, in flood-prone communities. This can potentially include both users who are already purchasing flood sensors of lower quality/effectiveness and those who previously had not adopted such technology.

The DHS Low-Cost Sensors Project has gone through two evaluation phases and is in the midst of the third and final one. It began with the identification of 10 firms for the initial development, winnowing the list to three firms for further development and testing, and then choosing a single firm for still further development and piloting in the field, and eventually testing commercial viability.

3. Baseline Analysis

High-cost and low-cost flood sensor systems are differentiated in three ways: The immediate hardware cost per unit of the sensor platform, the underlying infrastructure necessary for the hardware to function, and the personnel necessary to maintain the hardware and operate associated systems. The largest and most widespread high-cost flood sensor system in the United States is the federally-managed network of stream- and tide-gauges. These devices have relatively high hardware and maintenance costs per unit, rely heavily on sophisticated infrastructure up to and including orbiting satellites, and have considerable administrative overhead and personnel costs (Normand, 2019). Multiple federal agencies are involved in data monitoring, processing, and dissemination. The national Emergency Alert System and NOAA

Weather Radio can reach anywhere from 49 to 97 percent of the public in an emergency, especially during severe weather events including flooding (FEMA, 2018; NWS, 2019). Through the Advanced Flood Warning System, numerous states have entered into agreements with the federal government to operate and maintain their own portions of the network (NWS, n.d.). Other portions of the network are funded in part or in whole through private partnerships but are still managed by the U.S. Geological Survey (Normand, 2019).

Low-cost systems make use of the rapid pace of technological development to deliver reliable sensing capability using low-cost hardware, which keeps the equipment, operating, and maintenance costs low. These devices are cost-effective, generally do not rely on electrical grids for power, and make use of existing cellular and Wi-Fi network infrastructure to transmit data, meaning that the infrastructure to support these types of systems is generally already in place. More sophisticated low-cost networks may also use cloud computing or local server systems to handle data processing and network monitoring (Mousa et al., 2015; Mousa et al., 2016; Azid et al., 2015; Andersson & Hossain, 2015; Moreno et al., 2019). Low-cost flood sensor systems would therefore be attractive to communities that face greater-than-average flood risk but are not sufficiently covered by the high-cost federal network, or by communities that want a degree of redundancy in their flood warning systems. Additionally, rural areas facing greater-than-average risk of flooding could also be covered at a low cost, assuming adequate cellular network reception.

4. Cost Analysis

4.1. Program Overview

The Flood Inundation Sensor Program consists of three phases. In Phase 1, which extended from March to November 2016, 10 companies were provided with $100,000 each to develop specifications for flood sensors and to identify additional features that would enhance their capability. These features would include the ability to gauge rainfall and soil moisture, with various options calling for these features to be integrated or available as plug-ins to the sensors. Other aspects involved in design testing related to the power supply (solar or battery) and timing of sampling. The field was then narrowed to three companies: Evigia Systems, Inc., Physical Optics Corporation (POC), and Progeny Systems Corporation were selected as DHS S&T

partners on this project and were awarded Small Business Innovation Research (SBIR) funds to design, develop, and test their low-cost, deployable flood inundation sensors (DHS S&T, 2018).

Phase 2, which ended on August 30, 2019, involved beta-testing of sensors. A spinoff of Physical Optics Corporation, Intellisense Systems, Inc., was chosen to receive $750,000 to produce a prototype. Unlike the case of the Floodproofing Product/Standards Program, this does not involve any formal testing by a certifying organization, but rather involves distributing sensors to 300 stakeholders for field testing (Booth, 2019).

Phase 3, which extends from July 26, 2019 to July 25, 2021, focuses on product commercialization with the intent of being able to produce 1,500 to 2,000 sensors per week. At the outset, the federal government will pay for testing and evaluation. Commercial viability is likely to be enhanced by the fact that users of the sensors will be eligible for various types of federal assistance, including post-disaster funding from FEMA through its Public Assistance and Hazard Mitigation Grant Programs. Further adoption by the private sector is also likely, with expressions of interest already from security firms and retailers in both the U.S. and other countries (Booth, 2019).

4.2. Cost Overview

The program costs considered in this study are:

1. Research and development costs by government agencies and firms producing the flood sensors. We assume that the private sector R&D costs are factored into the selling price of the products. Thus, the R&D costs paid by government agencies include (all converted to 2017 dollars):
    - $1.02 million total for payments to the original 10 firms
    - $3 million for payments to the three semi-finalist firms
    - $0.72 million to Intellisense.
2. Product costs. This pertains to the sales price of the sensor product developed under this Program, which is estimated to be $1,500 per unit. This is an average of the original anticipated cost by S&T and the vendor’s cost estimate, factoring in uncertainties associated with a new product.

3. Installation costs. These are minimal because the sensors can simply be tied to telephone poles or bridge components.[13]
4. Operation and maintenance costs. These sensors will be operated using battery and solar charging, and, therefore, these operating costs will be small (the battery maintenance cycle can range from one to 10 years). We do, however, include the cost of Internet connectivity at $150 per sensor per year (Helmuth, 2019).

4.3. Cost Estimation

Low-Cost Sensor Program development costs are presented in Table 1. The several rows of the table correspond to potential research, development, and transition costs for such projects as identified in an initial CREATE study that developed a BCA methodology for DHS-related research projects (see, e.g., von Winterfeldt et al., 2019). The majority are not applicable to the case of the sensors project. The main cost item is DHS S&T and SBIR funding amounting to $4.74 million in 2017 dollars.

Individual product, installation, operation, and ancillary costs are presented in Table 2. Note that the product costs are estimated at a level of commercial viability that captures some economies of scale. The production target is 250 sensors per week for the first year, ramping up to 1,000 thereafter, with initial production beginning in 2020 (Helmuth, 2019). Note that the cost of adopting and implementing the low-cost flood sensors will dwarf the original public sector R&D costs.

[13] In general, the vendor provides mounting hardware for the upper communication portion. The lower flood sensor can be mounted either via concrete self-tapping bolt or zip-tied to a t-post that is hammered in the ground. Intellisense is still working on the details of this aspect for the final product and what to supply the customer. Any fence posts, t-posts, or conduit are not included as shipping would be cost prohibitive and as these products are readily available at commercial providers (Helmuth, 2019).

Table 1. Costs of Development and Testing of Low–Cost Flood Sensors

Cost Category	Start Date	End Date	Base Amount	Inflation Adj. 2017$	Source
Pre-project costs (R&D, non-DHS)			0	0	
Project costs DHS (S&T/SBIR)	March 2016	August 2019	4.75	4.74	S&T
Project costs (contractor cost share)					
Oversight cost at DHS (S&T/FEMA)			1.0	1.0	
Transition development cost					
TOTAL COST			5.75	5.74	

See explanation notes on cost definitions in von Winterfeldt et al. (2019).

Table 2. Product and Installation Costs of Low-Cost Flood Inundation Sensors (2017$)

Product	Unit	Product Cost	Installation Cost	Ancillary Cost	Operation Cost
Physical Optics Corporation -- *Intellisense*	Individual	$1,500	$10	$25	$150/year

5. Benefit Analysis

5.1. Overview

Table 3 summarizes the mechanisms of potential benefits from the implementation of improved warning systems. They essentially pertain to protecting or relocating property and people from flood harm and thereby reducing property damage, business interruption, and casualties. The table also summarizes the scope and limitations of each of the mechanisms.

This Program can yield benefits through the implementation of flood inundation sensors in three ways:

1. New sensors that can improve warning time and accuracy over existing products. This applies to the current set of users of sensors. Longer lead warning times can help

save lives by alerting people to the dangers of their current location and prompting individual or community relocation/evacuation. It can also provide additional time to install temporary flood barriers, move high-value contents, and implement community-wide mitigation like emptying storm drains or diverting streams. Finally, improved accuracy can reduce the cost of false alarms, and hence reduce the costs of unneeded evacuations and the time and effort to install temporary flood barriers.

2. Wider adoption of flood sensors. This applies to new users attracted by the products' enhanced ability to improve warning. Wider adoption of the new sensors is more difficult to estimate because the lack of data on the relationship between product improvements and adoption rates. One needs to consider the potential bias of the estimates received from vendors in the promotion of their products. We will utilize experiences with the introduction of previous generations of flood sensors as a check.
3. Potentially more cost-effective sensors. This applies to new users attracted by the potential lower cost of these products relative to those already in the market. The price of the various new sensors under the Flood Apex Program can be compared with similar products. Although the actual costs of the sensors depend on the specific configuration of the products, it is expected that these new sensors will cost about $1,500 per unit, which can be much less expensive than many flood sensors in use today.[14] We will evaluate these potential cost-savings, which will be added to the benefits side of the ledger.

[14] Sensors that meet U.S. Geological Survey standards are in extensive use and cost approximately $20,000 each. Many of their applications are for research purposes; the high degree of accuracy required for that sort of application is not needed for flood warning (Booth, 2019).

Table 3. Benefits of Enhanced Flood Warning

Protective Measure Mechanisms	Potential	Mechanism	Cost	Scope (Obstacle)
Protect Physical Assets (PD, BI)	Modest	Temporary Barriers; Community Measures	Low	Limited (Time)
Relocate Physical Assets (PD, BI)	Nearly Impossible	Mobility; High Value Contents	Moderate	Very Limited (Fixed in Place)
Relocate Production (BI)	Moderate	Branch Plants/Offices	Low	Limited (Subset of Firms)
Protect People (VOSL)	Modest	Temp Barriers; Elevate	Low	Limited (Time)
Relocate People (VOSL; BI)	Significant	Evacuation	High	Significant (Congestion)

Abbreviations: PD – Property Damage; BI – Business Interruption; VOSL – Value of Statistical Life

5.2. Methodology

The social cost of floods. Estimating the social cost of floods is a first step in quantifying the benefits of improved flood warning. Essentially, the benefits of this mitigation tactic are the societal costs prevented. These costs potentially come from several sources of loss caused by flooding in general, though with varying relevance to the case in point as noted in Table 2. Note also that some of the flood cost types, most notably business interruption (BI), have ripple, or multiplier, effects on both output and employment throughout the area affected by the flood and beyond (Rose, 2004). Note that this also applies to BI associated with evacuation, as well as imputed costs to households (Rose and Oladosu, 2008). The analysis would also take into account post-disaster resilience tactics to reduce these losses, such as the ability to make up lost production at a later date (Rose, 2017).

The most difficult aspect of this analysis is linking improved warning time and accuracy to the implementation of protective and relocation measures. We have conducted a review of the literature on the benefits of flood warning systems, which is summarized in Appendix B-1.[15]

Benefit estimation for low-cost flood sensors. Our investigation has identified two prime methods for estimating the benefits of warnings associated with low-cost flood sensors. The first, which might be termed "direct estimation," involves using data that combines the following considerations:

- Current flood warning times
- flood (property) damage and loss (of life and business) with current flood protection tactics and flood warning techniques
- flood warning improvements:
  - improved warnings (including lead time and accuracy of warnings)
  - lower-cost warnings

---

[15] We also note two other sources of information especially pertinent to estimating the benefits of flood hazard mitigation. The Flood Risk Assessment and Risk Reduction Plan developed by Charlotte-Mecklenburg Storm Water Services is used to assess flood risk for each property in the County, identify effective flood hazard mitigation techniques, and develop Flood Mitigation Priority Scores in order to prioritize individual properties (or property groups) for flood mitigation efforts (AECOM, 2012). The Benefit-Cost Analysis (BCA) Tool developed by FEMA is a standardized method for quantitative evaluation of the cost-effectiveness of disaster mitigation projects submitted under FEMA's Hazard Mitigation Assistance grant programs. Data required for using the Tool are extensive, and it is not possible for us to conduct BCAs for each individual property or mitigation project for this study; however, we do utilize some standard values and assumptions in the Tool.

- more warnings

- flood damage and loss reduction with tactics implemented in response to changes in warnings

If data were available for all of these considerations, we could implement the following set of results/calculations for an average community:

1. Access data on current warnings in the average community. Improvements would refer to both greater accuracy and increased warning time, though there is a trade-off between the two as noted below. Aside from any improvement in warnings, an increase in the number of sensors deployed is likely to stem from their lower cost, but benefits of costs and wider adoption would ideally be evaluated separately. Therefore, we defer discussion of the deployment of an increased number of sensors to a later section on technology adoption. Note that knowledge of the current warning level is not needed if improvements due to warning are expressed in percentage terms. If they are expressed in terms of warning levels (e.g., warning times), then current levels are needed because the relationship between warning time and reduction in losses is non-linear (see below).
2. Access data on flood damage/loss with current warning systems for the U.S. as a whole.
3. Access or estimate the average flood damage/loss with low-cost (and improved) warning systems (increased warning times) by type of flood damage/loss reduction tactic.
4. Subtract result #3 from result #1 to determine the improvement that can be brought about by implementing new low-cost flood sensors. If warning is not improved for the same number of sensors, then any increase in benefits is solely attributable to lower costs and/or wider adoption of sensors.

Data for Step #1 are available from the National Weather Service, which forecasts river streamflow and issues flood watches and warnings based on observations from the network of stream gauges operated by the U.S. Geological Survey, supplemented by weather radar and hydrological models. We use the National Weather Service's (2011) typical lead times for flood watches and warnings to inform our assumptions on current warnings in the average community.

Data on flood-related casualties (Step #2) are based on the 15-year averages of direct deaths and injuries, after adjusting for population growth, reported by the National Oceanic and Atmospheric Administration (NOAA)'s Storm Events Database (2019). Data on flood-related damages is based on the mean of the following three estimates: a) average damages reported by the Storm Events Database from 2004 to 2018 ($9.3 billion); b) average claims paid by the National Flood Insurance Program (NFIP) during the same period, adjusted for the percentage of at-risk homeowners covered by the program ($9.7 billion); and c) estimates from Quinn et al. (2019) spatial dependent models ($20.3 billion). Quinn et al. (2019) attribute the large discrepancy between their figures and other estimates to the fact that property owners affected by floods, particularly less severe floods, self-insure or fail to report losses if they believe it would affect property values or premiums.

Mean annual expected damages are likely to rise due to population growth and land-use changes. We assume an annual increase of 1.57 percent based on the average of two projections by Wing et al. (2018) for expected damages by 2050. That figure is derived by first estimating the increase in expected damages by 2025, assuming the annual increase in damages is linear. Expected damage is estimated to increase from 2017 to 2025 by 9.2 or 13.82 percent, depending on assumptions about population growth and migration to flood-prone cities. We use the average of those two projections (11.51 percent) to calculate the annual increase in expected damages.

Data for Step #3 pose the greatest difficulty. It ideally requires relating improved warning time to the effectiveness of individual flood damage loss reduction tactics,[16] primarily improvements in preparedness, such as community-based flood defenses, evacuation of people, relocation of physical assets where possible, shutdown of critical facilities, implementation of temporary flood barriers, etc. Note that these estimates involve a complex set of relationships—forecast accuracy, the translation of forecasts into warnings, or alerts,[17] the extent to which available risk reduction tactics will be implemented in the face of those warnings—none of which we can undertake ourselves. Most in-depth studies even finesse the latter consideration by simply assuming all risk reduction strategies will be implemented, in part because of the

[16] Note that in much of the flood warning literature, the term "pathways" is used rather than terms like "tactics" or "strategies" (Papenberger et al., 2015).
[17] In our analysis, we assume a flood "warning" triggers action. A lower information stage is that of a flood "watch," usually characterized by much lower degree of certainty about timing and location. Although the issuance of a flood watch provides further anticipatory information that can lead to improved risk reduction, we abstract from it.

complexity of the decision process. For example, Pappenberger et al. (2015, p. 279) note that: "In order for early flood warnings to be translated into decisions, clear mandates and responsibilities along the early warning chain from forecasted decision-maker must exist." Yet another complication is that longer warning times are desirable, but the optimal warning time also includes consideration of accuracy, which typically involves a period of waiting to attain a threshold level of probabilistic confirmation. One promising way to approach this is to use the "Day curve," which relates warning lead times (in hours) to percentage property damage prevented (see below).

The second approach is “benefits transfer,” which refers to the broad category of techniques using the concept of an analogy. That is, one adapts findings from another location, economic sector, and/or time period for the case in point. The technique ranges from simple adaptation, with some crude adjustments for size (population, economic activity) and time (economic growth or technological change), to the more sophisticated variant of what is known as benefit function transfer, where the analyst performs statistical analyses for one case or cases and applies the function to the case in point, filling in the values of explanatory variables. Data are not available for us to perform benefit function transfer, however, for this application.

The first approach above need not require our own estimation but rather the use of existing estimates based on primary data or simulations for the desired specific location or appropriate average locations. When this is not the case, or in the absence of primary data and statistical analysis or a simulation analysis of our own, the “benefit transfer” is the only alternative.

Many researchers have estimated the benefits of improved warning times, but many of these studies are limited to physical property damage rather than dollar value. Moreover, nearly all studies to date have failed to estimate the separate effects of all the various tactics that can reduce losses. Nor have they included all of the tactics, so even the use of an aggregate estimate, which is all that would be required for our study, would have some limitations before noting still others. For example, many of these estimates are performed for non-applicable areas (such coastal areas subject to flood surge) or non-applicable countries (foreign countries with much different building stocks). The most promising of such results relates to the work of Priest et al. (2011), Verkade and Werner (2011), and Pappenberger et al. (2015) (see Appendix Table B-1). The studies use a combination of primary data and data transfer methods. Unfortunately, they tend to be for areas outside of the U.S., though with likely similar physical structures. Moreover, the baseline improved warning times are likely to differ from those in the U.S.[18] These characteristics make the use of these results for benefit transfer on our part more tenuous.

Finally, while the existing literature acknowledges that flood warnings reduce injury and loss of life by enabling evacuations and search and rescue operations (Penning-Rowsell et al., 2005; Priest et al., 2011) and allowing potential victims to seek shelter (Jonkman & Vrijling, 2008), few studies have quantified that effect or its relationship to lead warning time.

Another set of applicable findings to which we can use for the first approach or to which to apply benefit transfer are the results of the application of the FEMA hazard loss estimation tool, HAZUS-MH. Below, we briefly summarize the necessary data and some potential steps to use HAZUS data, parameters or results to estimate warning time, baseline damage/loss, or the effectiveness of various flood damage/loss reduction tactics.

Relationship between warning time and damage reductions. The Day curve depicts the relationship between flood warning time (in hours) and the potential damage reduction in percentage terms with respect to the total maximum flood damages. It was first developed based on the property distribution, value, and property owners' historical response rate to warnings in the Susquehanna River Basin (Day, 1970). The original Day curve, presented in Figure 5.9 of the HAZUS Flood Model Technical Manual, assumed a 100 percent public response rate and a maximum loss reduction rate of 35 percent to both structure and contents. In HAZUS, users can enter the warning time in hours to apply a variation of the Day curve to estimate damage reductions. In addition, the users also have the option to adjust the 35 percent maximum damage reduction assumption. One factor that affects this assumption would be whether there are flood-protection measures in place (such as sandbags or other temporary flood barriers).

[18] This matters because the relationship between damage/loss reduction and warning time is not linear. In fact, it is likely to have a logarithmic shape, i.e., incremental damage/loss reduction is likely to decline with increased warning time.

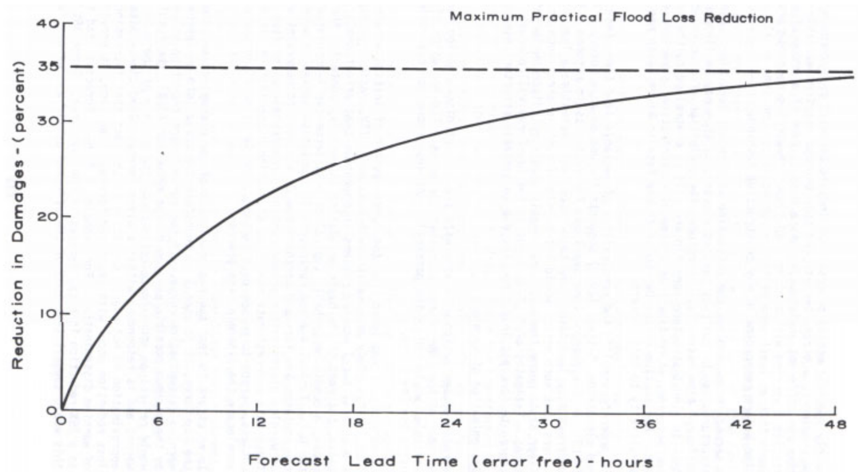

Figure 5.9 Day Curve for Residential Areas (Source: USACE, New York District, 1984)

Source: HAZUS Flood Model Technical Manual

There have been many examples of applications and modifications of Day curves. The New York District of USACE modified the original curve based on the specific conditions of the Passaic River Basin in 1984. The modifications include considering the specific relationship between building locations and forecast lead time, incorporating the average speed of warning dissemination, and capping the public response rate at 85 percent (USACE, 1994).

The Institute for Water Resources (IWR) has stated reservations on applying the original Day curve without accounting for the differences in residential structures since 1970s (USACE, 1994). It also suggested an alternative approach as to shift the depth-damage curve by 0.3 or 0.6 meters to account for the warning time. However, the report did not specify the relationship between the warning time and the corresponding shift (Carsell et al., 2004).

The Flood Hazard Research Center (FHRC) of Middlesex University in UK developed a more comprehensive methodology to evaluate the damage-reducing effect of flood warning systems in relation to warning time, depth of flood, and a few other factors. First, the damage reduction estimates for residential buildings by warning time and flood depth were based on the study by Chatterton and Farrell (1977) (see Figure 4). However, these curves reflect the optimal damage reduction potentials, assuming that all property owners are notified and that all take rational and efficient actions after receiving the warnings. In order to take other factors into account, the following equation for actual flood damage avoided, D_a, was proposed by FHRC (Carsell et al., 2004):

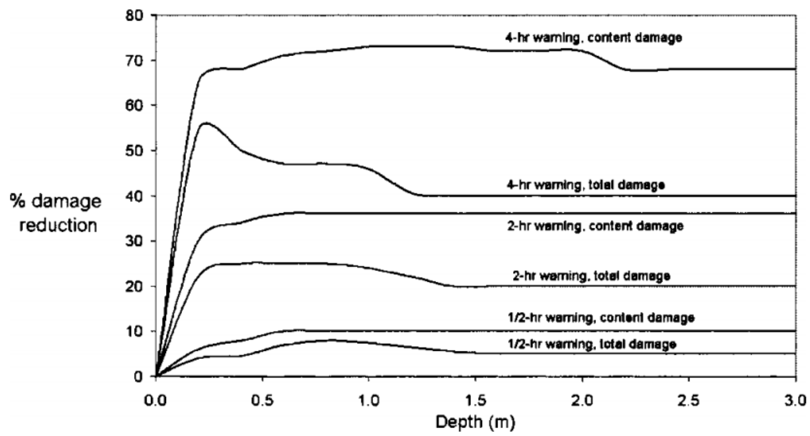

Fig. 4. Damage-reduction estimates for residential structures (Chatterton and Farrell 1977)

Unfortunately, this modification requires more data than were available to us.

Benefits of lower-cost sensors. Gains to consumers also arise from the availability of lower cost flood sensors. The USGS uses sensors, primarily for research purposes, that cost approximately $20,000 per unit. More general-purpose sensors are currently available for around $4,000, and thus there is the potential for a $2,500 per unit savings from the availability of the new low-cost sensors developed from DHS funding. Because not all additional and potential users will adopt the sensors because of the lower price, we will be using a rule of thumb determined by von Winterfeldt et al. (2019) of utilizing only one-half of the potential savings.

5.3. Technology Adoption

The benefits of flood sensors are highly dependent on the extent to which the new technology and products are adopted. The fact that adoption of flood sensors may help reduce National Flood Insurance Program claims may be a good starting point. However, adoption is likely to extend beyond those structures and contents damaged to a broader set of owners of structures who are concerned about flood damage. We will explore several options, some noted below, and also consider using a reasonable range of upper- and lower-bound adoption scenarios.

Note also that adoption by the public sector may only be the beginning of the stream of benefits from the development of low-cost sensors. Security firms such as ADT have expressed an interest, as have retailers such as Walmart and Costco. In addition, interest has been expressed by potential clients in other countries, such as Australia (Booth, 2019).

The vendor plans to demonstrate the capacity to produce 250 units per week in the first year (2020) and scale the capacity to 1,000 units per week in the following years. These projections translate to a total production of 469,800 sensors over the 10-year period from 2020 to 2029.[19] If we assume that on average each customer (a community or business) needs 60 sensors to establish an enhanced flood monitoring and warning system, the total number of sensors produced in the 10-year period will meet the needs of 7,830 entities.

The National Weather Service (NWS) (2017) has a certification known as StormReady that indicates whether a community has taken the following steps:

- Create a system that monitors weather conditions locally
- Establish a 24-hour warning point and emergency operations center
- Have more than one way to receive severe weather warnings and forecasts and to alert the public
- Promote the importance of public readiness through community seminars
- Develop a formal hazardous weather plan, which includes training severe weather spotters and holding emergency exercises

[19] The 10-year timespan assumes that improved technology will be available after 10 years, thus making it the "effective life" of the product.

Table 4. Assumptions for Key Variables Affecting Adoption of Low-Cost Sensors

	Lower-bound	Base Case	Upper-bound
# of years of product life[a]	5	5	10
# of NWS certified counties/parishes	1,452	1,452	1,452
% of NWS certified counties likely to adopt	70%	80%	90%
additional adoption by non-certified counties as a % of # of NWS certified counties/parishes	5%	10%	20%
# of additional non-certified counties/parishes adopting[b]	73	145	290
# of communities & businesses within each county that purchase the sensors	2	3	4
# of customers	2,178	3,920	6,389
# of sensors per customer	20	60	100
# sensors needed	87,120	470,448	638,880

[a] Assumed to be same as in the lower-bound case to obtain a result that is close to the total number of sensors projected by vendor to be produced in the 10-year horizon.
[b] Assumes 5%, 10%, 20%, respectively, of the number of NWS certified counties for the lower, base and upper cases.
[c] Assumes a 10-year product life.
[d] Assumes a 5-year product life.

As of October 29th, 2019, the NWS reported that 1,452 of the 3,142 counties and county-equivalent bodies are StormReady certified. FEMA (2019) provides a data visualization tool based on NOAA Storm Event Database data, which indicates that 98 percent of all U.S. counties or equivalents, roughly 3,080 counties, were impacted by at least one flooding event between 1996 and 2016.

Table 4 presents assumptions for the base case, lower-bound, and upper-bound values of key variables that we use to calculate the total market demand for the Intellisense sensors in a 10-year horizon.

In the base case, our estimated number of sensors to be purchased roughly matches the vendor's total production for the next 10 years.

6. Net Benefits, Benefit-Cost Ratio, and Return on Investment

Three categories of benefits can arise from the implementation of low-cost flood sensors:

1. Casualties. Sensors are especially helpful in warning against flash floods, a major cause of deaths and injuries. Penning-Rowsell et al. (2005) estimate that moving from an inadequate warning system to a tried and tested system and adopting emergency plans reduces loss of life by 6.5 percent. We conclude that an improvement in lead

warning time will likely reduce casualties by a lower amount but use the 6.5 percent reduction as our upper-bound assumption. Based on 15-year averages of annual deaths and injuries resulting directly from floods, we assume the following values of loss of life and injury prevention for the three cases examined:

Loss of life prevention:

Lower-bound: 2

Base Case: 4

Upper-bound: 6

Injuries prevention:

Lower-bound: 2

Base Case: 3

Upper-bound: 5

In estimating the benefits of casualties prevented, we follow the Environmental Protection Agency (EPA, 2015) guideline that the value of a statistical life (VSL) is $10 million in 2016 dollars. We assume all flood-related injuries are of moderate severity—equivalent to a concussion or major abrasion—and that the cost of such an injury is 4.7 percent of the VSL (FAA, 2016). Thus, each injury prevented is valued at $47,000 in 2016 dollars.

2. Property damage. Although structures cannot be moved even if warnings of impending floods are improved, warnings can help protect them. This protection ranges from the installation of low-cost, typically temporary flood protection products (see the separate report on low-cost flood barriers by Wei and Rose in this Appendix) to communitywide measures such as stream diversion and emptying urban sewer drains. In addition, automobiles and high-value contents vulnerable to floods can be moved. To estimate the damages prevented by enhanced warning, we utilize the Day curve described in Section 4.2 above.

   The major assumptions involved are:

   a. The availability of low-cost sensors reaps benefits by:

      Case A: improved lead time for users that already employ warning systems

      Case B: increased adoption of sensors where there are none in place currently

For Case A, we assume that 80 percent of the NWS-certified counties will adopt the new sensor. For Case B, we assume that the additional adoption by non-certified counties will be 10 percent of the number of NWS-certified counties.

b. Average current warning time:

Case A: where local warning systems already exist: 18 hours

Case B: where local warning systems do not exist (entities are dependent on long-distance warning): 6 hours

c. Improvements in warning time are as follows for both cases:

Lower-bound: 10 percent

Base Case: 25 percent

Upper-bound: 40 percent

3. Cost savings. Table 5 presents the calculations for the cost-savings related to the Intellisence sensors. The calculations differ for the two cases. Those users that already have a sensor network (Case A) are considered to benefit from the entirety of the cost savings. Those users that do not currently have a sensor network, are considered to benefit from only half of the cost-savings, as explained above. The total cost savings over the life of the sensors are a large amount of more than $1.1 billion.

Table 5. Cost Savings of Intellisense Sensors

	Per Unit				Total	
	Original Price	Intellisense Price	Cost Saving	Adj Cost Saving	# of Sensors	Total Cost Savings
Case A	$4,000	$1,500	$2,500	$2,500	427,680	$1,069,200,000
Case B	$4,000	$1,500	$2,500	$1,250	42,768	$53,460,000
Total					470,448	$1,122,660,000

4. Evacuation benefits of two types:

a. More evacuations

b. Fewer false positive evacuations

Note that estimates of evacuation benefits are not included in the analysis at this time. However, it is safe to say that they would not increase our benefit estimates by more than 10 percent, and likely much less.

The 18-hour average current warning time assumed in Case A is derived by averaging the ranges of typical lead times for flood warnings, given as 6 to 12 hours by the National Weather Service, and flood watches, given as 6 to 48 hours by the National Weather Service (NWS, 2011). These averages are 9 hours and 27 hours for warnings and watches, respectively. The 6-hour average current warning time assumed in Case B is derived by using the minimums for those ranges.

Application of the Day curve indicates an 18-hour warning time can reduce damages by 26.22 percent. This figure is a bit lower than the lower-bound in the literature of approximately 35 percent (see, e.g., Papenberger et al., 2015). We consider the estimate is reasonable because the vast majority of the literature focuses on much larger warning systems. Combining the Day curve and the assumptions above results in the values that are inputs into our estimation process as presented in Table 6.

Benefit-cost analysis – base case. We combine our property damage reduction assumptions and estimated levels with our previous set of assumptions for key variables affecting the adoption of low-cost sensors to estimate the benefits presented in the Table 7 below. Note that total costs include the program costs and the installation cost of sensors. Total benefits include life safety and reduction in property damage. If we consider the benefits of the increased utilization of low-cost sensors only in relation to program costs, we would obtain a benefit-cost ratio (BCR) of nearly 275.3:1, with a return on investment of 27,433 percent. However, it is more appropriate to estimate the BCR in relation to the cost of implementing the sensors, which yields a BCR of 2.7 and a rate of return on investment of 174.8 percent. Note that the BCR is lower than the BCR for risk reduction tactics for floods estimated in the Mitigation Saves 1 and Mitigation Saves 2 reports (MMC, 2005; Rose et al., 2007; MMC, 2017). The main reason is that both studies included a broader range of flood hazard reduction options. For example, the original MMC study included buying out properties in areas of repetitive flooding, which had a very large BCA.

Table 6. Property Damage Reduction Assumptions and Estimated Levels

Property Damage Reduction	Lower Bound	Base Case	Upper bound
Existing Local Warning Systems			
Improved Lead Times	10%	25%	40%
New Damage Reduction Levels	27.11%	28.29%	29.35%
Improved Reduction	0.89%	2.07%	3.13%
New Local Warning Systems			
Improved Lead Times	230%	275%	320%
New Damage Reduction Levels	27.11%	28.29%	29.35%
Improved Reduction	11.1%	12.28%	13.34%

Table 7. Base Case Analysis of the Benefits of Flood Sensors

Variable	**Base Case**
Project Cost (S&T/SBIR)	4,739,546
Pre-project Cost (S&T)	1,000,000
Transition Development Cost	1,000,000
Total Program Cost	6,739,546
Cost per Sensor (includes installation/ancillary)	1,685
# of Sensors Needed	470,448
Total Cost of Sensors and Ancillary Equipment	792,704,880
Average Annual Property Damages Caused by Floods in Baseline	13,100,000,000
Projected Average Annual Increase of Baseline Property Damages by Floods	1.57%
Increased % of Avoided Property Damage from Improved Lead Time	2.1%
Increased % of Avoided Property Damage from More Coverage	12.3%
Benefit of Reduced Property Damage from Improved Lead Time in Year 10	113,537,613
Benefit of Reduced Property Damage from More Coverage in Year 10	84,193,351
Total Benefit of Reduced Property Damage in Year 10	197,730,963
Reduction in Cost per Sensor (Comparing to Other Effective IoT Sensors)	2,500
Benefit from Cost Savings in Year 10	121,368,649
Benefit of Life Safety in Year 10	40,000,000
Benefit of Reduced Injuries in Year 10	141,000
Discount Rate	3%
Ten-year Discounted Benefits	1,855,588,063
Ten Year Net Benefits	1,180,230,017

7. Sensitivity and Uncertainty Analysis

A sensitivity analysis was undertaken using the values of variables summarized in Table 8, and based on the discussion in previous sections. Note that the upper-bound values of sensor adoption in the Table are consistent with the projections by the vendor of the product.

The estimated net benefits associated with the Flood Apex Low-Cost Sensors are especially sensitive to some of the assumed parameters, primarily on the benefits side (see Tables 8 and 9, and Figures 1 and 2 below). Figure 1 presents the “tornado diagram,” which shows how changes in the underlying input parameters affect the net benefit estimate of the low-cost flood sensors. In the tornado diagram, the length of the bar for each input variable represents the range of the 10-year net benefits calculated by using the low and high values of this variable while holding the other variables at the base values. The most important parameters are those with the longest bars in the diagram. The sensitivity analysis indicates that the largest uncertainty comes from the assumptions of reduction in costs of the new flood sensors compared to other alternative IoT sensors. Other important variables include the discount rate and percentage of NWS-certified counties that will adopt the new sensors.

To explore the uncertainty associated with the estimates of the 10-year net benefits, we conducted a Monte Carlo simulation. We assume triangular probability distributions for all variables listed in Table 8, using the low and high values as the minimum and the maximum, respectively, of the triangular distribution, and the base case value as the mode. Next, 10,000 simulations were run to obtain the distribution of the 10-year net benefits as presented in Figure 2. The 5th, 50th, and 95th percentiles, as well as the mean and median of the distribution, are presented in Table 9. The uncertainty analyses on these variables indicate a median net benefit of \$1.14 billion, with a 5th percentile of \$0.77 billion and a 95th percentile of \$1.66 billion.

Table 8. Ranges of Variable Values for Flood Sensors

Input Variables	Low	Base	High
Pre-project cost (S&T)	0	1,000,000	2,000,000
Transition development cost	0	1,000,000	2,000,000
Cost per sensor (including installation/ancillary/operation costs)	1,155	1,685	2,395
Reduction in Cost per Sensor (comparing to other effective IoT Sensors)	1,500	2,500	3,500
% of NWS certified counties likely to adopt	70%	80%	90%
Additional adoption by non-certified counties as a % of # of NWS certified counties/parishes	5%	10%	20%
# of communities & businesses within each county that purchases the sensors	2	3	4
Projected average annual increase of baseline property damages by floods	1.27%	1.57%	1.87%
Improved reduction in property damage from improved lead time	0.9%	2.1%	3.1%
Improved reduction in property damage from more coverage	11.1%	12.3%	13.3%
Product life (in years)	5	5	10
Number of sensors purchased per customer	20	60	100
Annual life-saving in Year 10	2	4	6
Annual reduced injuries in Year 10	2	3	5
Discount rate	0%	3%	7%

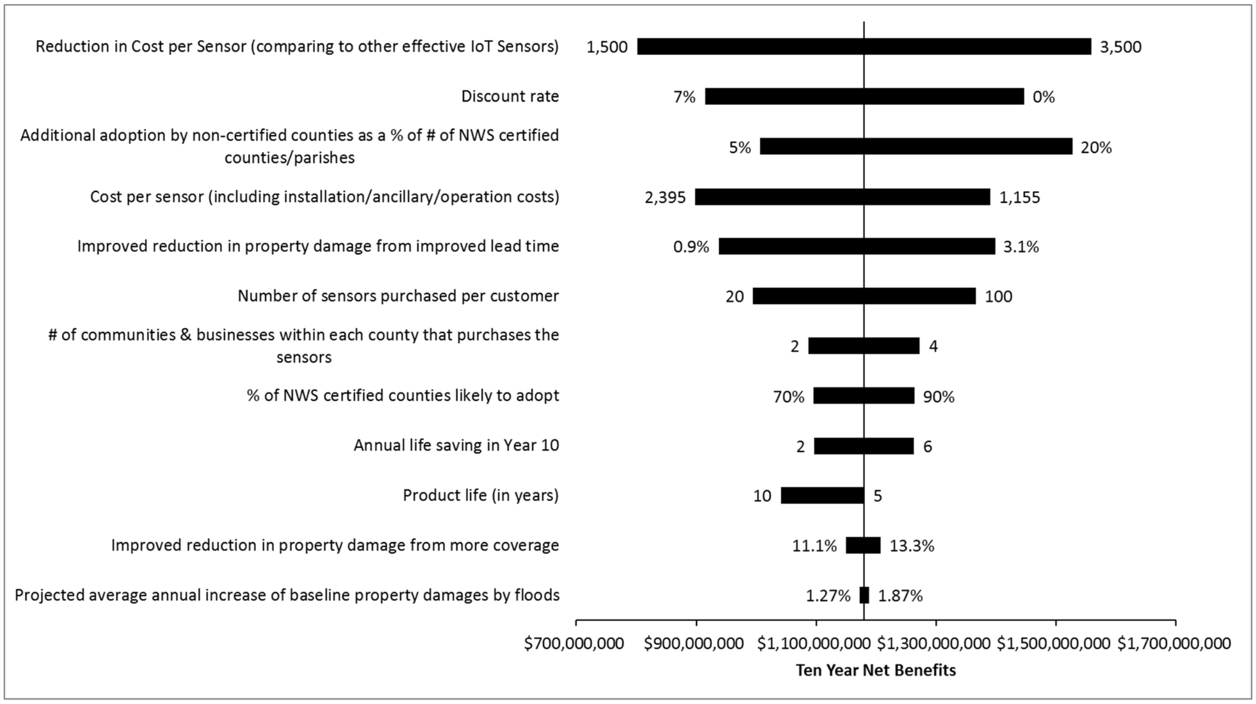

Figure 1. Tornado diagram for 10-year net benefits of flood sensors

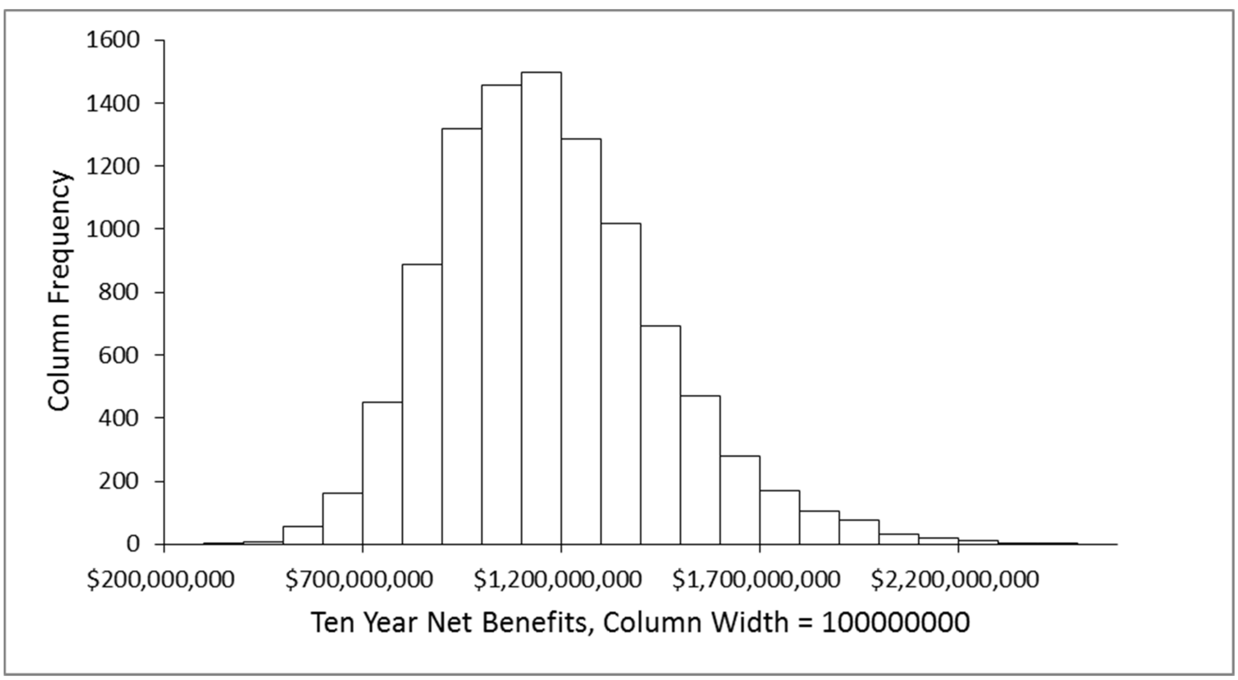

Figure 2. Distribution of 10-year net benefits of flood sensors

Table 9. Statistics of the Net Benefits Distribution

Mean	$1,169,292,031
St. Dev.	$276,175,660
5th Percentile	$767,345,304
25th Percentile	$973,306,562
Median	$1,143,651,529
75th Percentile	$1,336,922,957
95th Percentile	$1,663,164,553

8. Assumptions and Limitations

Many assumptions have had to been made thus far in our analysis. The next steps will be to vet our assumptions, which will likely involve a recalibration of the numerical values of some of them. We will depend on a more thorough examination of literature and input by experts in government, industry, and academe. The major assumptions are listed below.

- Total DHS program cost: $5.74 million
- Per-unit sensor cost: $1,155, $1,685, $2,395

Benefit estimation:

- Average current warning time (Case A and Case B): plus and minus 25 percentage points
- Improvements in warning time (Case A and Case B): 10 percent, 25 percent, 40 percent

Technology adoption:

- # of years of product life: 5, 10
- # of counties adopting: 73, 145, 290
- # of communities/large businesses within each county that purchases the sensors: 2, 3, 4
- # of sensors per customer: 20, 60, 100

9. Additional Research

Future research can be conducted in several areas to improve the precision of the low-cost flood inundation sensor analysis:

1. Currently, we project the adoption of the sensors based on a set of assumptions on the percentages of the NWS-certified and non-NWS-certified counties that will deploy the new sensors, as well as the likely number of communities/businesses within each county of adopting. The total number of sensors demanded based on these assumptions in the base case is similar to the vendor's projection of its future production capacity within a 10-year time frame. After Phase 3 of the project, which focuses on commercialization of the product, more research on market penetration of the new sensors and the communities' awareness of this low-cost and effective warning option should be conducted. This will improve the accuracy of the estimate on the actual deployment of this new product.
2. We assumed in the study that the deployment of the new sensors can increase the warning time of any existing warning systems by 25 percent in the base case. This estimate can be improved if data on the field-testing results of the new sensors can be collected. Specifically, the warning time provided by the new sensor products can be compared to the average flood warning time those participating communities have currently using their old warning systems.
3. Future research is needed to evaluate how the deployment of the new sensors can provide more accurate warnings and thus effectively reduce the cost of false positive alarms.
4. Quantification of additional benefits of these sensors should be pursued. Other benefits include: better data coverage for calibration and validation of hydrodynamic forecast models, and use in stormwater engineering, analysis, and design projects. These sensors can act as data-gap fillers between the existing federal/state networks (i.e. NOAA and USGS tide/stream gauges). Other benefits include a reduction in the number of unnecessary evacuations due to inaccurate flood predictions.

All of these considerations suggest that our results should be considered a lower bound of benefit estimates.

10. References

AECOM. 2012. *Flood Risk Assessment and Risk Reduction Plan*. Report to Charlotte-Mecklenburg Storm Water Services. Available at: https://charlottenc.gov/StormWater/Flooding/Documents/Flood_RARR_Plan-Final.pdf.

Alexander, D. (2019). Personal Communication with Director of the DHS Geospatial Management Office, DHS S&T.

Andersson, K., & Hossain, M. S. (2015). Heterogeneous wireless sensor networks for flood prediction decision support systems. *Proceedings - IEEE INFOCOM*, *2015-August*, 133-137.

Azid, S., Sharma, B., Raghwaiya, K., Chand, A., Prasad,S., Jacquier, A. (2015). SMS Based Flood Monitoring and Early Warning System. *ARPN Journal of Engineering and Applied Sciences*, *10*(15), 6387-6391.

Booth, J. (2019). Personal Communication with Director of the Geospatial Management Office, DHS S&T.

Carsell, K. M., Pingel, N. D., & Ford, D. T. (2004). Quantifying the benefit of a flood warning system. *Natural Hazards Review*, *5*(3), 131-140.

Chatterton, J. B., and Farrell, S. J. (1977). *Nottingham Flood Warning Scheme: Benefit Assessment*. *Rep.* Prepared for Severn-Trent Water Authority.

Congressional Budget Office (CBO). 2019. *Expected Costs of Damage from Hurricane Winds and Storm-Related Flooding*. Available at: https://www.cbo.gov/publication/55019.

Cumiskey, L., Priest, S., Valchev, N., Viavattene, C., Costas, S., & Clarke, J. (2018). A framework to include the (inter) dependencies of disaster risk reduction measures in coastal risk assessment. *Coastal Engineering*, *134*, 81-92.

Day, H. J. (1970). *Flood Warning Benefit Evaluation-Susquehanna River Basin (urban residences)* (ESSA Technical Memorandum WBTM Hydro-10). Prepared for the Weather Bureau. https://www.nws.noaa.gov/oh/hdsc/Technical_memoranda/TM10.pdf

Department of Homeland Security Science and Technology Directorate (DHS S&T). (2017, May 25). *Smart Alerts Pilot Project.* https://www.dhs.gov/sites/default/files/publications/Flood-Apex_Smart-Alerts-Pilot-Project-Fact-Sheet-170525-508.pdf

Department of Homeland Security Science and Technology Directorate (DHS S&T). (2018). *Internet of Things (IoT): Low-Cost Flood Inundation Sensors.* https://www.dhs.gov/sites/default/files/publications/IAS_IoT_Low-Cost-Flood-Inundation-Sensors-FactSheet_180629-508.pdf

Environmental Protection Agency (EPA). (2015). *Regulatory Impact Analysis of the Final Revisions to the National Ambient Air Quality Standards for Ground-Level Ozone*. https://www3.epa.gov/ttnecas1/docs/20151001ria.pdf

Federal Aviation Administration (FAA). (2016, September). *Treatment of the Values of Life and Injury in Economic Analysis.* https://www.faa.gov/regulations_policies/policy_guidance/benefit_cost/media/econ-value-section-2-tx-values.pdf

Federal Emergency Management Agency (FEMA). (2013). *HAZUS-MH Flood Model Technical Manual*. https://www.fema.gov/media-library-data/20130726-1820-25045-8292/hzmh2_1_fl_tm.pdf

Federal Emergency Management Agency (FEMA). (2018). *2017 National IPAWS EAS Test Final Report*. https://www.fema.gov/media-library-data/1523303270960-0ddf8c45ca3eac68c4a4256c39da431c/2017_IPAWS_EAS_National_Test_Final_Report_FINAL.pdf

Federal Emergency Management Agency (FEMA). (2019). *Data Visualization: Historical Flood Risk and Costs*. https://www.fema.gov/data-visualization-floods-data-visualization

Helmuth I. (2019). Personal Communication with Program Lead, Intellisense Systems, Inc., Torrance, CA.

Jonkman, S. N., & Vrijling, J. K. (2008). Loss of life due to floods. *Journal of Flood Risk Management*, *1*(1), 43-56.

Lightbody, L. 2017. *Flooding Disaster Cost Billions in 2016*. PEW Center, Washington DC.

Loftis, J. D., Forrest, D., Katragadda, S., Spencer, K., Organski, T., Nguyen, C., & Rhee, S. (2018). StormSense: A New Integrated Network of IoT Water Level Sensors in the Smart Cities of Hampton Roads, VA. *Marine Technology Society Journal, 52*(2), 56-67.

Molinari, D., & Handmer, J. (2011). A behavioural model for quantifying flood warning effectiveness. *Journal of Flood Risk Management*, *4*(1), 23-32.

Moreno, C., Aquino, R., Ibarreche, J., Pérez, I., Castellanos, E., Álvarez, E., ... & Clark, B. (2019). RiverCore: IoT device for river water level monitoring over cellular communications. *Sensors*, *19*(1), 127.

Mousa, M., Oudat, E., & Claudel, C. (2015). A novel dual traffic/flash flood monitoring system using passive infrared/ultrasonic sensors. *Proceedings - 2015 IEEE 12th International Conference on Mobile Ad Hoc and Sensor Systems*, 388-397.

Mousa, M., Zhang, X., & Claudel, C. (2016). Flash Flood Detection in Urban Cities Using Ultrasonic and Infrared Sensors. *IEEE Sensors Journal, 16*(19), 7204–7216.

Multihazard Mitigation Council (MMC). (2005). *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*. National Institute of Building Sciences, Washington, DC.

Multihazard Mitigation Council (MMC). (2017). *Mitigations Saves: Interim Report.* National Institute of Building Sciences Washington, DC.

National Oceanic and Atmospheric Administration (NOAA). (2019). *Storm Events Database* [Data file and code book]. https://www.ncdc.noaa.gov/stormevents/

National Weather Service (NWS). (2011). *National Weather Service Reference Guide.* Silver Spring, MD: National Weather Service.

National Weather Service (NWS). (n.d.). *Advanced Flood Warning System Partners*. https://water.weather.gov/afws/afws_partners.php

National Weather Service (NWS). (2017, July 31). *StormReady and TsunamiReady*. https://www.weather.gov/about/storm-tsunami/

National Weather Service (NWS). (2019, February 21). *NOAA Weather Radio All-Hazards*. https://www.weather.gov/ilx/nwr

Normand, A.E. (2019) U.S. Geological Survey (USGS) Streamgaging Network: Overview and Issues for Congress. Congressional Research Service R45695. https://fas.org/sgp/crs/misc/R45695.pdf

Pappenberger, F., Cloke, H. L., Parker, D. J., Wetterhall, F., Richardson, D. S., & Thielen, J. (2015). The monetary benefit of early flood warnings in Europe. *Environmental Science & Policy*, *51*, 278-291.

Penning-Rowsell, E., Floyd, P., Ramsbottom, D., & Surendran, S. (2005). Estimating injury and loss of life in floods: a deterministic framework. *Natural Hazards, 36*(1-2), 43-64.

Priest, S. J., Parker, D. J., & Tapsell, S. M. (2011). Modelling the potential damage-reducing benefits of flood warnings using European cases. *Environmental Hazards*, *10*(2), 101-120.

Quinn, N., Bates, P. D., Neal, J., Smith, A., Wing, O., Sampson, C., … Heffernan, J. (2019). The Spatial Dependence of Flood Hazard and Risk in the United States. *Water Resources Research*, *55*(3), 1890-1911.

Rose, A. (2004). Economic Principles, Issues, and Research Priorities in Natural Hazard Loss Estimation. In Y. Okuyama and S. Chang (Eds.), *Modeling the Spatial Economic Impacts of Natural Hazards* (pp. 13-36). Heidelberg: Springer.

Rose, A. (2017). Economic Resilience to Terrorism and Natural Disasters. In A. Abbas, M. Tambe and D. von Winterfeldt (Eds.), *Improving Homeland Security Decisions* (pp. 193-219). New York: Cambridge University Press.

Rose, A. & Oladosu, G. (2008). Regional Economic Impacts of Natural and Man-Made Hazards Disrupting Utility Lifeline Services to Households. In H. Richardson, P. Gordon and J. Moore (Eds.), *Economic Impacts of Hurricane Katrina,* Cheltenham: Edward Elgar.

Rose, A., Porter, K. Tierney, K. et al. (2007). "Benefit-Cost Analysis of FEMA Hazard Mitigation Grants," *Natural Hazards Review*, 8, 97-111.

U.S. Army Corps of Engineers (USACE). (1994). *Framework for Estimating National Economic Development Benefits and Other Beneficial Effects of Flood Warning and Preparedness* (IWR Report 94-R-3). https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/94-R-3.pdf

Verkade, J. S., & Werner, M. G. F. (2011). Estimating the benefits of single value and probability forecasting for flood warning. *Hydrology and Earth System Sciences*, *15*(12), 3751-3765.

von Winterfeldt, D., Farrow, S., John, R., Eyer, J., Rose, A., and Rosoff, H. (2019). Assessing the Benefits and Costs of Homeland Security Research: A Risk-Informed Methodology with Applications for the U.S. Coast Guard, *Risk Analysis*, forthcoming.

Wing, O. E. J., Bates, P. D., Smith, A. M., Sampson, C. C., Johnson, K. A., Fargione, J., & Morefield, P. (2018). Estimates of present and future flood risk in the conterminous United States. *Environmental Research Letters, 13(*3): 034023.

Appendix Table B-1. Literature Synthesis of Flood Warning Studies

Study	Location	Warning System or Technology	Annual Cost	Damages Prevented: Methods	Pathways	Estimates[a]	BCRs	Comments
Cumiskey et al. (2018)	Varna Bay, Bulgraia & Praia de Faro, Portugal	disaster risk reduction (DRR)		incorporate interdependencies between "DRR measures in coastal risk assessment by distinguishing between primary and non-primary measures on risk reduction"				
DHS S & T (2017)		Smart Alerts Pilot Project						
Loftis et al. (2018)	Hampton Roads, VA	StormSense	\$3,000/sensor \$4,400/radar unit			sensor accuracy: ±5 mm ±18mm		
Molinari & Handmer (2011)				behavioral model using event tree				

Moreno et al.	Colima,	RiverCore		message queuing	measures:			
(2019)	Mexico			telemetry transport	peak-flow depth			
				protocol	underground sound			
					mean flow velocity			
					surface velocity			
					flow depth			
					ground vibration			
					basal forces			
					fluid pore pressure			
					impact force			
Pappenberger	Europe	European	41.8 M Euros	probabilistic	flood defenses	32%		155:1
et al. (2015)		Flood	*21.8 M for*	forecasting with	watercourse maint.	0.9%		4:1
		Awareness	*four centers*	standard weighted	community defense	0.36%		2:1
		System	*20 M over 10*	annual average	moving/evacuation	5.7%		28:1
		(EFAS)	*years for*	damage values	warning resistance	0.0036%		0.02:1
			maintenance		early warning	32.85%		159:1
Priest, Parker,	England	no specific		flood warning		England	Grimma,	
& Tapsell	& Wales	tech		response benefit		& Wales:	Germany	
(2011)				pathways	flood defenses	28%	n/a	
		part of		(FWRBP)	watercourse maint.	10%	5%	
	Grimma,	Floodsite			community defense	1%	1%	
	Germany	project			moving/evacuation	5%	5.8%	
					business continuity	5%	6%	
					resilience measures	2%	3%	

Verkade & Werner (2011)	Scotland	flood forecasting, warning and response systems (FFWRS)	hydro-economic model of expected annual damage combined with relative Economic value ("dimension -less factor" to scale between "no warning"/"perfect warning" cases)	warning lead times	1 hour: 2% 2 hours: 3% 3 hours: 3% 4 hours: 9% 5 hours: 11% 6 hours: 11%

[a] Percentage reduction in cost of floods (property damage only in most studies unless otherwise noted).

Benefit-Cost Analysis of Observed Flood Extent (OFE)[20]

Analysts: Jonathan Eyer and Juan Machado

October 2019

1. Summary

Description. The Observed Flood Extent (OFE) program uses Landsat global satellite imagery to provide information about how frequently water was present in a given location. OFE classifies each pixel in these satellite images to identify whether water was present at the time the image was taken using multispectral analysis. Each pixel is observed on multiple wavelengths so that multiple characteristics that are associated with the presence of water can be detected (e.g., water-stressed plants, evapotranspiration). Because it provides a more precise identification of the presence of water than traditional satellite imagery, OFE could be used to alert homeowners who are not aware that they are in a flood-prone region of their risk and allow them to reduce their exposure.

Results. In the baseline case, OFE results in positive 10-year expected net benefits of approximately $18.4 million. These benefits are driven by property owners reducing their exposure to contents losses during flooding events, and much of the benefits are derived from reducing damages from small but more frequent floods rather than large, infrequent events. While the benefits of OFE in reducing damages are large, this is offset by increased expenditures from property owners on mitigation. The benefit-cost ratio inclusive of property owner expenditure is 1.1, and the return on investment is 10 percent. Because OFE relies on individual property owners making decisions about increasing mitigation, and because property owners will not make these investments if the benefits do not exceed the costs, the potential losses from OFE are limited. The project itself is relatively inexpensive in comparison to the mitigation expenditure, so the bulk of potential costs can be avoided by the property owners declining to invest in more mitigation. Across a sensitivity analysis, over half of the simulations suggested that OFE would result in no changes in mitigation on the part of property owners and the program would lose its full $8 million investment. There are substantial potential benefits, though; the 75th and 95th percentiles are $26.7 and $142.1 million, respectively. On average, the

[20] The authors are grateful to Konstantinos Papaefthymiou for his excellent research assistance.

possibility of these large benefits outweighed the more likely outcome of modest losses, and the average net present value was $22.4 million.

2. Description of the Project

Increased information about disaster risks allows property owners to make better informed mitigation decisions. If property owners had previously underestimated the risks that they face, this will result in lower damages as they will now take more defensive steps to limit losses. On the other hand, if property owners had overestimated their risks, they will reduce their mitigation and realized damage will increase when floods do occur. In both cases, though, property owners are better off with the increased information. In the former, they have adopted mitigation opportunities that are cheap relative to the benefits they provide, and in the latter, they have ceased to spend on costly mitigation that does not justify its investment.

The Observed Flood Extent (OFE) project uses global satellite imagery to provide information about how frequently water was present in a given location. By counting the number of times that water was observed since 1973, OFE provides a measure of the frequency with which water was present on given patches of land. In contrast, existing methods of understanding flooding risk and prevalence may either be more geographically aggregated or require complex and costly hydrological modeling.

This information could be used by property owners in flood-prone areas to make more informed flood mitigation decisions because the OFE flood information is more geographically disaggregated than the alternative FEMA flood maps that would otherwise inform flooding risks. As an additional consideration, OFE provides information about the historical evidence of water. This means that OFE can detect flood events even in areas that have only recently been developed and that were not subject to recordkeeping during past flood events.

The project was conducted by MDA Information Systems under a contract with the Department of Homeland Security. The OFE program uses Landsat global satellite imagery to provide information about how frequently water was present in a given location (MDA Information Systems, 2016). Landsat, the world's longest-running satellite imagery program, consists of a series of satellites operated by NASA and the U.S. Geological Survey (USGS) that provide terrestrial imaging. Since 2008, the USGS has provided free access to all Landsat images dating back to 1972, which has allowed many projects to use this imagery for a diverse range of applications (Woodcock et al., 2008).

OFE classifies each pixel in these satellite images to identify whether water was present at the time the image was taken using multispectral analysis. Each pixel is observed on multiple wavelengths so that multiple characteristics that are associated with the presence of water can be detected (e.g., water-stressed plants, evapotranspiration). This provides a more precise identification of the presence of water than traditional satellite imagery. For example, during storms, cloud cover might prevent satellite imagery from identifying flooding conditions. By relying on multispectral imagery of vegetation stress caused by the flooding, the previous flooding conditions can be detected even after flooding has receded.

By counting the number of times that water was observed since 1973, OFE provides a measure of the frequency with which water was present on given patches of land. Importantly, the Landsat images, and therefore the OFE values, are available in undeveloped areas, so historic flood events can be detected even when there was no land development that would justify recording the flooding. This means that OFE could be used to alert homeowners who are not aware that they are in a flood-prone region of their risk and allow them to reduce their exposure (Botzen et al., 2019; Radiant Solutions, 2018). The initial OFE project was conducted using 11 areas of interest throughout the United States.

One benefit of programs like OFE for providing information is that they can be scaled relatively cheaply because the detection is algorithmic. This means that once the multispectral characteristics that are associated with water are identified, the algorithm can be applied to any region and automatically detect the historic presence of water with little additional guidance from the modelers.

3. Baseline Analysis

Without information from the OFE program, property owners rely on the existing, available information about their exposure to floods. In regions that have been previously mapped for flooding studies, property owners can observe risks based on FEMA flood risk maps (e.g., 100-year flood plains or 500-year flood plains) and make their decisions about mitigation behavior based on that information. The expected damage from flooding is determined by the mitigation behavior of property owners and the true risks of flooding facing the property.

Over the previous 10 years, there have been about $3.1 billion in NFIP claims per year on average. These losses are driven by the existing mitigation decisions of the impacted households based on the information they have available about risks as measured by flood zones. Using data from Houston's experience during Hurricane Harvey as a proxy for the general applicability of the information from OFE, 14 percent of all impacted claims could have benefited from the information provided by the OFE program. This suggests that nationwide, there are around $434 million in annual NFIP claims for properties that may benefit from OFE. Note that these losses are evaluated under the existing level of information available to property owners (i.e., property owners are aware that they are in a region that is not zoned as being at greatest risk for flooding).

Table 1 shows the average number of claims, number of policies, average amount per claim, and average total amount of claims associated with the NFIP in the last 10 years and over the entire timespan of available data (1978 to present).

Table 1. NFIP Policy and Claims Summary

	Average Number of Claims Paid	Average Policies in Force	Average Claim Amount (2017 Dollars)	Total Annual Claims (2017 Dollars)
All Available Years	44,647	3,798,390	$33,589.58	$2,083,342,209.11
Last 10 Years	53,347	5,418,653	$46,662.91	$3,104,541.14

4. Cost Analysis

Because the Landsat database which underlies the OFE data is publicly available, the actual cost of generating the OFE product is relatively low. The cost of the pilot project was approximately $260,000 (in 2017 dollars), which was paid to MDA Information Systems, a private contractor. These costs were associated with salary for staff scientists and include a 12 percent labor fee. This work relates to identifying the linkages between the multispectral Landsat imagery and the presence of standing water, crop stress consistent with recent inundation, and other signals of flooding. MDA Information Systems estimates that OFE can be expanded at a cost of approximately $1 per square kilometer, meaning that the entire country can be mapped for a cost of approximately $8 million (MDA Information Systems, 2016). There is no information available about the costs incurred by the government for oversight of MDA during the pilot project, but given the low total expenditure on the pilot, any oversight costs are likely to be low.

While the behavioral changes induced by OFE will cause property owners to incur costs if they change their mitigation behaviors, these expenditures are not incorporated into the cost portion of the analysis because they are dependent on the uptake of the mitigation. These expenditures are discussed in the benefits analysis section.

5. Benefit Analysis

This paper highlights several important considerations related to understanding the costs and benefits of information-based research and development. First, increased technological advancements mean that information can be identified at a geographically disaggregated level at low marginal cost. While previous estimations of risk at the geographic specificity provided by OFE would have required specific geographic modeling in each grid, these methodological advancements mean that patterns can be identified on test data and scaled up to a much larger area of interest. Second, there is an important consideration related to the incidence of costs when research is provided that influences individual decision-making. Many of the parameters underlying the benefits and costs are uncertain to the person who is modeling the costs and benefits, but the actual decision-makers have more information and less uncertainty. Because these decision-makers will rationally opt not to change their behavior if the benefits do not outweigh the costs, the total losses from a project are, at most, the amount spent to develop the information. No expenditure will take place on the part of individual decision-makers if the information does not make them better off.

The OFE project shows an interesting case of this consideration. While the model parameters suggest that it is likely that OFE will result in no changes to behavior and no reductions in flood damages, the expected benefits of the program are positive. This is because people will spend on mitigation if the information afforded by OFE will reduce their expected losses but will otherwise avoid the expenditure. A similar effect should be considered in the case of all programs designed to generate information to induce behavioral changes. At worst, there will be no behavioral change. At best, however, there may be substantial benefits.

Benefits of OFE information. Where natural disasters are relatively frequent, the damages from each natural disaster tend to be smaller than in regions where they are less frequent after controlling for the actual magnitude of the disaster (Hsiang and Narita, 2012; Neumayer, 2014; Bakkensen and Mendelsohn, 2016). Information about exposure to natural disaster risks is critical for making mitigation and adaptation decisions that will influence losses in the event of a disaster.

The value of the OFE program is driven by the benefits of the information that OFE provides. In the case of OFE, these benefits relate primarily to the expected damages from flooding. The value of information is calculated by assuming that decisions about uncertain events are made optimally given the set of information that is available, and the benefit of information is the change in expected outcomes with and without the new information. In general, this can be expressed as

$$Value\ of\ Information = \int_0^\infty D(x;m)f(x) - D(x;m,I)f(x)dx\,.$$

The function *D(x; .)* expresses the damage from an event of a particular magnitude (e.g., flood height) and will vary depending on whether additional information, *I*, is available. In the absence of the additional information, decisions are made using only the existing information, and m. *f(x)* is the probability that an event of magnitude, *x*, occurs.

OFE provides additional information beyond the FEMA-designated flood plain status, allowing better-informed decisions which can in turn reduce damages from a disaster (i.e., increasing mitigation efforts). The general format of the value of information can be expressed in the case of OFE as

$$Individual\ Value\ of\ OFE = \int_0^\infty [D(flood\ magnitude; flood\ plain) - D(flood\ magnitude; flood\ plain, ofe)]f(flood\ magnitude)\ dflood\ magnitude - [Mitigation\ Cost(flood\ plain, ofe) - \ MitigationCost(flood\ plain)].$$

Note that this introduces an additional consideration. OFE generates benefits by prompting changes in mitigation behavior by individual property owners. While these changes can result in reductions in damages, they also result in increased costs borne by the property owners. One interesting consideration related to OFE is that while increased mitigation expenditure due to these induced changes could be quite high, the net benefits for individuals are guaranteed to be non-negative. If the increased costs from adopting new mitigation measures exceeded the reduction in expected losses, the property owners would choose not to adopt the new mitigation.

Measuring the change in damages with OFE. OFE data is not already available to property owners so it is not possible to observe how the information about flooding risk will influence mitigation behavior and the associated losses from floods. Information about flood zones are used as a proxy to identify how increased knowledge about flooding risks will impact flood damages. I estimate the impact of the actual flood information that households have available to them (i.e., whether they are in a 100-year flood plain or not) to measure the benefits of risk information. Like the OFE program, the flood plain status provides a signal to homeowners about how likely it is that a flood event will strike their property.

Estimates of flood damages are based on National Flood Insurance Program (NFIP) claims in Houston, Texas and the surrounding area related to Hurricane Harvey in 2017. Houston was selected as a study area because it experienced the largest flooding event among regions for which OFE data was available. NFIP claims associated with Hurricane Harvey are estimated based on characteristics of the flood facing each property and the FEMA flood zone classification associated with the property. A classification of "A" indicates that a property is within a 100-year floodplain, while an "X" indicates that a property is either within a 500-year floodplain or is not designated as being in a floodplain.

There were approximately 79,000 flood insurance claims under the NFIP associated with Hurricane Harvey in Texas. Around half of these claims are associated with properties that were not zoned A, meaning the property owners were not previously told that they were in a 100-year flood zone. The average total claims were not statistically different between properties that are in Zone A and those that are in Zone X. When claims are differentiated between claims associated with contents and those associated with building damage, an important dichotomy appears. Table 2 shows the average claims for building and content losses in Houston for losses associated with Hurricane Harvey. Average building damage claims are approximately $3,000 higher in properties that are in Zone A, consistent with these properties being likely to experience greater flooding due to more exposure to flood waters. Average contents damage claims are approximately $3,000 higher in properties that are in Zone X. Homeowners in these regions are ostensibly less aware of the risks that they face from flooding than those who are in Zone A and less likely to undertake defensive actions, such as moving high-value contents.

Table 2. NFIP Claims in Houston by Zone

	Zone X	Zone A
Contents Claim	$41,852.90	$38,177.59
Building Claim	$109,081.55	$112,983.60
Total Claim	$150,934.50	$151,161.10

The reliance on NFIP data comes with an important caveat. Information about losses under NFIP are only available for households that have opted into the flood insurance program. This means that, at a minimum, the 50 percent of high-risk homes that opt not to purchase flood insurance (Dixon et al., 2006; Landry and Jahan-Parvar, 2011) are omitted. There is also a critical selection element regarding who purchases flood insurance. On one hand, property owners who purchase flood insurance may be at greater risk for flooding than those who do not have flood insurance in a way that is not observable. This would mean that the reliance on the NFIP data would result in overestimates of average benefits because NFIP households have greater risk and greater potential benefits from new information. On the other hand, property owners who purchase flood insurance may be more risk averse and thus more likely to react to new information.

The amount of each flood claim is estimated as

$$floodclaim_i = \alpha * \ zoneA + \beta * floodheight_i + \ \epsilon_i.$$

In this specification, the coefficient α represents the difference in flood claims for homes that are zoned "A" (high risk) relative to those that are zoned "X" (low risk), controlling for characteristics of the house and characteristics of the flood at the location of the home. The control for flood characteristics is the mean height of flood waters during Hurricane Harvey in each census tract.

Table 3. Regression Results

	Contents Claims			**Building Claims**		
Zone X	2300.25 (1409.94)	4886.31*** (1109.69)	6875.54*** (1365.13)	-10980.67*** (4680.40)	-6001.67 (4264.65)	36.16 (4638.92)

Flood Height	-214.35 (606.57)	107.02 (329.21)	505.60) (438.49)	61.19 (1373.38)	-13.08 (938.61)	1348.02 (1312.51)
Location Control	Zip Code Fixed Effects	City Fixed Effects	Smooth Spatial Polynomial	Zip Code Fixed Effects	City Fixed Effects	Smooth Spatial Polynomial
Adjusted R2	0.22	0.15	0.08	0.30	0.21	0.12

Table 3 presents the impact of being in Zone X on the value of contents claims due to Hurricane Harvey. The first three columns correspond to the impact of being in Zone X on claims for contents damages, while the latter three columns correspond to building damages claims. Each dependent variable is presented under a series of alternative controls for unobserved geographic variation. There is evidence that contents claims are indeed higher in properties that are zoned X relative to those that are in Zone A, which are ostensibly at greater risk. There is no evidence of this relationship for building damages. Under the coarsest geographic controls, there is evidence that properties that are in Zone X have much lower building damage than those that are in Zone A, and under other specifications, there is no statistically significant difference between damages in Zone A and in Zone X. This provides evidence that the mechanism influencing losses is the fact that those who are told that they are at greater risk from floods take precautionary actions to protect their belongings but are unable to take enough investments to the structure to outweigh the underlying increased risk to the property. The mid-point estimate suggests that content claims for properties that were in Zone X were $4,886.31 higher than properties in the same city that experienced flood waters at the same height that were in Zone A.

Measuring changes in expected losses. The previous regression results correspond to losses for a single disaster – Hurricane Harvey. In practice, many of the mitigation behaviors that can be adopted will reduce damage resulting not only from large disasters like Harvey, but from some smaller ones as well. On the other hand, the benefits of mitigation do not appear with certainty. If no flood takes place, there are no loss reductions induced by the mitigation. The expected benefits from OFE would be the sum of benefits for each flood magnitude multiplied by the likelihood that a flood magnitude occurs, summed over all the potential flood magnitudes.

Farrow and Scott (2013) estimate losses from floods under a continuous range of flood return periods in Baltimore, Maryland. They calculate flood losses using the HAZUS model and estimate a reduced-form model of losses as a function of flood return period. Under the assumption that loss reductions from mitigation due to OFE information scale proportionally to overall losses, the benefits of OFE-induced mitigation can be calculated across the entire range of potential return periods. For example, if a 50-year flood results in one-quarter of the damages that a 100-year flood causes, OFE would result in one-quarter of the impact for a 50-year flood relative to a 100-year flood. By setting the OFE benefits from the econometric results ($4,886 reduction in contents damages) to the impact of OFE on Hurricane Harvey, a 100-year flood event, it is possible to estimate the impact of OFE mitigation on all magnitudes of flooding events (Emanuel, 2017).

The aggregate benefits across multiple return periods can be expressed as a function of the parameter from Farrow and Scott (2013), the minimum and maximum affected return rates, and the benefits from OFE for a 100-year event.[21] One key parameter here is the minimum flood return period for which OFE information is effective in reducing losses. For example, while small, annual floods can be damaging in aggregate, it is unlikely that OFE will inform property owners of additional risk if they already experience the floods frequently. Table 4 shows the annualized reduction in losses due to OFE under varying assumptions about the minimum flood magnitude for which OFE is effective in providing additional information. The benefits decline rapidly as more frequent flooding events are removed from consideration because, while the actual damages from frequent floods are small, the aggregate damages (and potential benefits) compound.

[21] I am grateful to Scott Farrow for providing the mathematical formulation underpinning this result.

Table 4. Annualized Reduction in Losses by Minimum Flood Return Period

Minimum Return Period (years)	1	5	10	15	25
Annualized Benefits	$2016	$593	$345	$250	$165

Measuring the number of affected houses. OFE will only be useful for at-risk properties that were not previously aware of the flood risk. Figure 1 shows the distribution of flood plain designations in the Houston area at the census tract level. Census tracts are defined as being either in the 100-year flood plain (Zone A) or not (Zone X) based on which zone occupies a larger area according to existing flood hazard maps. Figure 2 shows the distribution of OFE designations in the Houston area at the census tract level. As shown in the figures, a substantial portion of the properties that do not lay in the 100-year flood plain – in which property owners could potentially view themselves as being at low risk from flooding – have been observed to flood in the past. This suggests that a substantial portion of property owners who are not in a designated 100-year flood plain could benefit from the information contained in OFE.

I define properties as having the potential to benefit from OFE if they are in a census tract that is (1) primarily in Zone X and (2) has an OFE value above 1 (i.e., the average number of times a pixel in a tract was identified as having water exceeded 1). Among the NFIP claims associated with Hurricane Harvey, approximately 61 percent were in census tracts primarily outside of a 100-year flood plain. Of these properties, 77 percent lay in tracts that were not detected as having previously contained water using the OFE algorithm. The remaining 23 percent of Zone X properties were identified by OFE as having previously experienced a flooding event. This indicates that about 14 percent of all properties that filed claims due to Hurricane Harvey could have had improved information if OFE had been available.

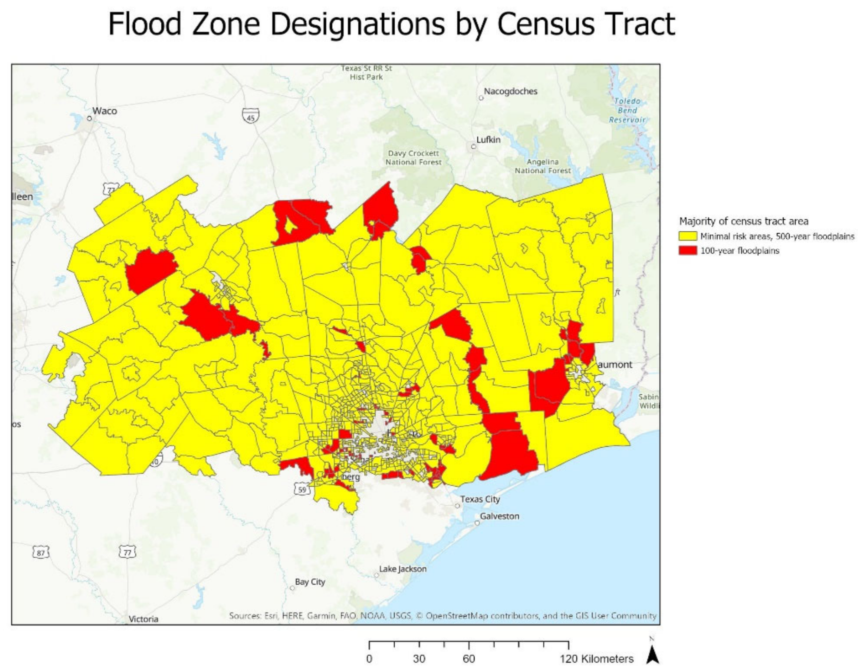

Figure 1. Flood plain status of census tracts by majority of area

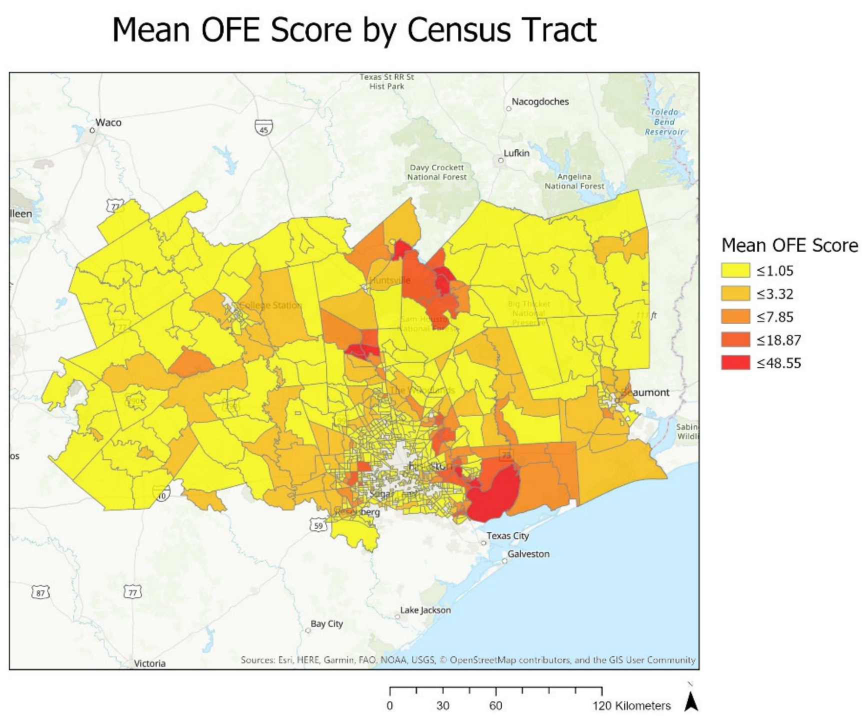

Figure 2. Mean OFE score of census tracts

These ratios can be applied to the entire population of flood insurance policy holders to calculate the aggregate number of homeowners who could benefit from the OFE information.

Between 2009 and 2018, there were, on average, 5.4 million NFIP policies in effect nationwide. Under the assumption that the nationwide accuracy of OFE and flood plains is comparable to that of Houston, this means that around 760,000 households that currently have federal flood insurance are at greater risk from flooding than their flood zone status suggests and that OFE could provide additional information.

In practice, this is almost certain to overestimate the benefits from this information. Many property owners who are at risk from floods already ignore available risk-management alternatives. Participation in the NFIP program is, at most, around 50 percent of potentially impacted households (Dixon et al., 2006; Landry and Jahan-Parvar, 2011) meaning that many homeowners fail to adopt a low-cost (and often subsidized) risk management alternative even when it is available. Uptake rates for properties outside of the designated Special Flood Hazard Areas (SFHAs) are even lower. Because the benefits of OFE are associated with identifying risks for property owners who are outside of these designated flood zones, the true proportion of households that change their behavior due to OFE information will likely be lower than the 50 percent who buy flood insurance in designated high-risk areas. Only 3 percent of households nationally have flood insurance. Under a range of responses between 2 percent and 8 percent, there will be between 17,500 and 90,000 property owners throughout the country who undertake additional mitigation based on the information provided by OFE.

Again, there is an important caveat related to the reliance on NFIP data. The new information provided about risk might cause some households that do not currently have flood insurance to adopt flood insurance due to the increased information about their risks. This would increase both total claims when floods occur as well as the number of households that could mitigate in response to the OFE information (it would also increase NFIP revenues from paid premiums).

6. Net Benefits, Benefit-Cost Ratio, and Return on Investment

Household benefit-cost. Under the baseline parameters, the information provided from OFE results in expected benefits of $345 per property per year for properties that uptake additional mitigation due to the information provided by OFE. This results in approximately $3,000 in benefits over a 10-year time horizon per property that reacts to OFE.

The benefits of OFE are driven by assumptions that homeowners will adopt new mitigation investments because of the increased information about their risks. These mitigation strategies are likely to result in privately borne costs as homeowners make changes to their property to defend against flooding risks. These costs must be weighed against the loss reductions from mitigation.

The regressions are consistent with loss reductions in damages to contents rather than damages to the building itself. This means that rather than requiring costly retrofitting (e.g., stilting), the damage reductions from OFE are likely to be lower cost. Wet floodproofing retrofitting costs range between $1.70-3.50 per square foot, meaning costs of $3,400-$7,000 for a 2,000 square foot home (FEMA, 2015). Still, many of these wet flood-proofing strategies are more closely aligned with reducing building damage than reducing the damage to contents. For example, one wet flood-proofing strategy relates to allowing flood water to flow through the basement to preserve structural integrity. In reality, many of the relevant mitigation alternatives are likely to be relatively low cost or even costless. For example, outlets could be elevated, or valuables could be moved to the second story from the first story. To account for this, the wet flood-proofing estimates from FEMA (2015) are halved for a mitigation cost range of $1,700-$3,500.

An important consideration in valuing the information from OFE is that while the costs of mitigation may exceed the benefits from mitigation, it is unlikely that OFE will result in substantial net losses. While the costs of mitigation and some of the benefits of mitigation are uncertain, the final decision to invest in mitigation or not is made by the household which has more information. For example, while there is uncertainty about how much a mitigation strategy would cost (e.g., raising outlets above ground-level), the homeowner will have no uncertainty about this cost at the point that she speaks to a contractor. Thus, if the expected costs of mitigation exceed the expected benefits, the mitigation will not be undertaken. This means that at the individual-level, there is no downside from OFE. At worst, the property owners will simply make no changes in their mitigation behavior.

Aggregate benefit-cost. The total benefit-cost analysis of OFE from the perspective of DHS is determined by the aggregate change in net household expenditure and the cost of the program itself. The net benefits of the program are

$$Net\ Benefits = \sum_i (Damage\ Reduction_i - Mitigation\ Expenditure_i) - Program\ Cost$$

where Damage Reduction and Mitigation Expenditure is summed over all of the households who respond to OFE, and Program Cost is the expenditure to develop OFE ($8 million nationally).

Under the baseline parameters, this indicates aggregate 10-year net benefits of approximately $18.4 million. There is a total reduction in contents claims of approximately $190 million, but much of this is offset by the increased mitigation expenditure. When costs are viewed only from the perspective of government expenditure ($8 million), the benefit-cost ratio is 23.6, and the return on investment is 2,262 percent. When the mitigation costs that are incurred by individuals are included as well, the benefit-cost ratio is 1.1, and the return on investment is 10 percent.

7. Sensitivity and Uncertainty Analysis

Most notably, as the minimum flood return period for which OFE information is effective in reducing losses increases, the benefits of OFE decline dramatically. This is because while extreme events are quite damaging and have the greatest potential benefits from increased mitigation, they are rare. By contrast, smaller events that happen much more frequently cause more damage in the long-run.

Break-even analysis. These benefits are sensitive to several parameters and assumptions in the model. Holding all other input parameters constant, the aggregate OFE investment breaks even if mitigation costs do not exceed the private, discounted benefits from additional information (mitigation cost = $2,900). Similarly, OFE breaks even if the information is effective in mitigating against storms with a return period of at most 11 years or if the benefits of the OFE information applied to a 100-year return period event are at least $4,400. In each case, these values are relatively close to the baseline parameter values, so there is a strong possibility that the individual benefits from increased mitigation will not exceed the private costs and there will be no additional mitigation induced.

Tornado and sensitivity analysis. Figure 3 presents a tornado analysis of the net present value of the OFE project. This diagram highlights the important nature of individual decision-making in the analysis. The left side of the tornado diagram (losses) are small relative to the right side (gains). Because individuals make adoption decisions based on whether the mitigation will benefit them, the losses are capped at $8 million. On the other hand, the benefits are potentially quite large. The most important driver of this variability is the minimum effective flood return rate. As the information from OFE becomes more effective at reducing losses from frequent, small events, the benefits from OFE grow. Conversely, under the assumption that OFE information will defend against only infrequent events, OFE leads to losses of $8 million. The cost of increased mitigation per home and the expected damage reduction from a 100-year event also cause variation in the net present value of OFE benefits, but these impacts are small relative to the variability in the minimum effective flood return rate. The percentage of homes that will respond to the OFE information results in some variability in the net present value of OFE, but it is quite small compared to the other input variables.

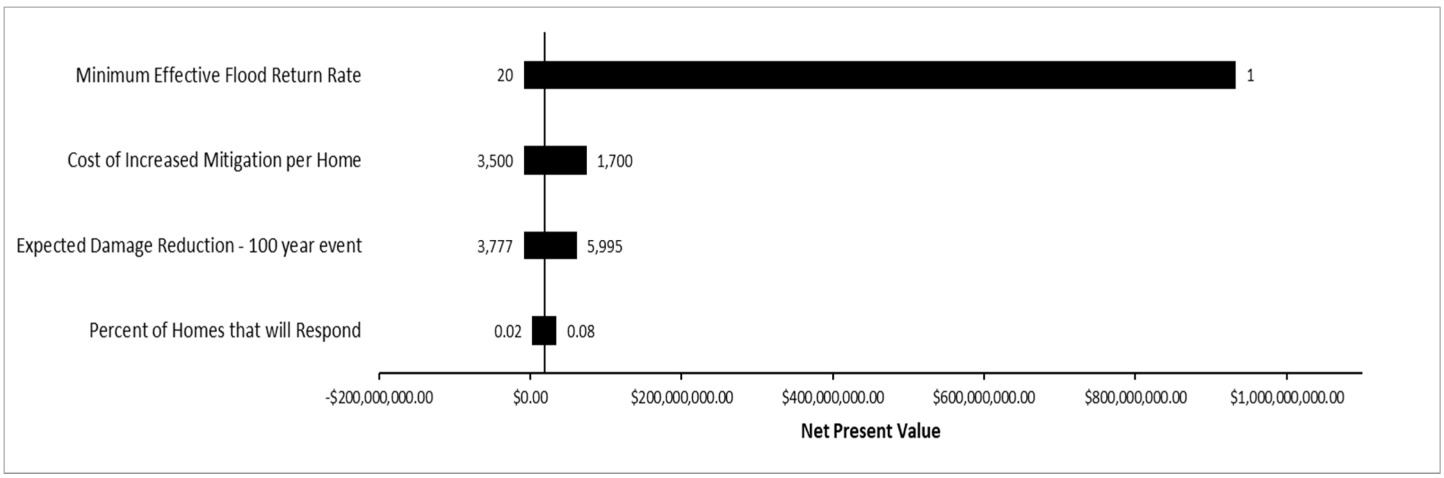

Figure 3. Tornado analysis of input variables to the benefits model

Uncertainty analysis. Table 5 shows the range of values for the key input parameters in the sensitivity analysis. Figure 4 shows the distribution of net benefits from OFE across a series of 10,000 simulations under a range of input parameters. Table 6 presents the summary statistics for the net present value of the OFE program across these simulations. Over half of the simulations result in net losses of $8 million, indicating that no private mitigation takes place. The 75th percentile and 95th percentile are $26.7 and $142.1 million, respectively.

Table 5. Range of Input Values for the Sensitivity Analysis

	Low	Baseline	High
Cost of Increased Mitigation per Home	$1,700	$2,600	$3,500
Expected Damage Reduction - 100-year event	$3,777	$4,886	$5,995
Minimum Effective Flood Return Rate	1	10	20
Percent of Homes that will Respond	0.02	0.05	0.08
Number of Properties w/ Flood Insurance	3,798,390	5,418,653	5,133,785

Table 6. Summary Statistics of Net Present Value of the Sensitivity Analysis

Mean	$22,440,373
Standard Deviation	$62,812,634
5th Percentile	-$8,000,000
25th Percentile	-$8,000,000
50th Percentile	-$8,000,000
75th Percentile	$26,737,849
95th Percentile	$142,179,760

This highlights an important consideration about OFE and government-funded research that results in individual responses in general. The majority of the simulations reveal that OFE will result in a net loss of $8 million, the full cost of developing OFE throughout the contiguous United States. Under these scenarios, the benefits of reducing flood damages are low relative to the costs of mitigating and individually rational households that opt not to invest in more mitigation. Still, the average benefits across all the simulations are positive. This is because the benefits from OFE have a long right tail, meaning that there are some situations in which the information derived from OFE will result in very large benefits. For example, if the private costs are much lower than the $3,600 baseline mitigation used in the modeling, many households will undertake mitigation and reap substantial aggregate benefits on the order of hundreds of millions of dollars in damage reduction. While it is unlikely that the benefits are this high, the magnitude of the benefits in these scenarios outweighs the more frequent cases in which OFE results in a slight loss.

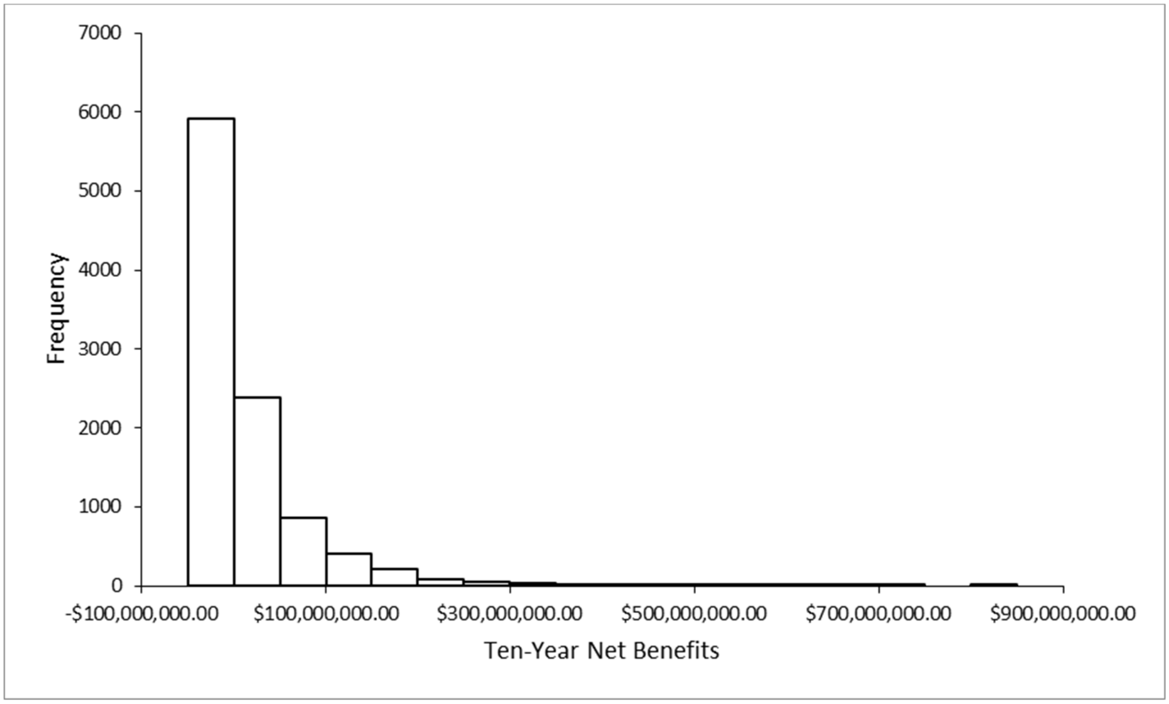

Figure 4. Distribution of 10-year net benefits

8. Assumptions and Limitations

The analysis of the costs and benefits of OFE require several important assumptions. First, the benefits of OFE are predicated on the basis that individual property owners will be able to rationally observe the impacts of increased mitigation on their properties and make mitigation decisions accordingly. This assumption drives the fact that potential losses from the OFE program are capped at the $8 million expenditure required to scale the program nationally. If property owners are not fully informed or rational about the costs and benefits of mitigation on their properties under the new OFE information, this assumption would not hold, and people could undertake mitigation investments that do not result in benefits that exceed their costs.

It is also important to note that the damages and the number of impacted households are drawn from information about the NFIP. Only a portion of households opt into the NFIP, so potentially there are property owners who would benefit from OFE but who are not captured in the data. This would lead to an underestimate of the potential benefits of OFE. Similarly, the information from OFE will provide a signal to some property owners that they are at greater risk than they initially believed. This could serve to increase the number of properties that are covered under the NFIP program as people who believed they were at low risk are informed that their properties may flood. On a related note, not all flooding damages are captured in the NFIP data, even for those properties that have flood insurance. Some flood damages may not result in a claim, for example, or may result in damages that exceed the level of coverage. Again, this would bias the estimated benefits of OFE downward.

Finally, the analysis of the benefits of OFE was based on the assumption that the program is expanded nationally. The analysis of the damages and the proportion of properties that will potentially benefit from OFE information, though, was based only on one region, and these values were extrapolated to a national sample. In actuality, the damages and potential mitigation benefits will vary spatially, as will the proportion of properties that are zoned as low risk that OFE will identify as high risk.

9. Additional Research

Future study should expand the econometric estimates of how variation in information impacts flood damages. This should incorporate both geographic variation and variation in flood magnitudes. While data on NFIP flood claims are readily available for a range of flooding events, the difficulty in expanding the study scope to include more regions will be in obtaining detailed information about flood heights for other events. Future study should also incorporate more spatial resolution in measuring flood damages. While the NFIP collects information about flood claims at the address-level, these data were unavailable.

The analysis can also be expanded to include the decision about whether or not to purchase flood insurance. The above analysis was conducted based on the impact of OFE on only property owners who had flood insurance. A comparable exercise should be conducted to estimate how information about flood risk impacts the likelihood of having a policy. This could be conducted using the NFIP policies dataset.

Finally, the analysis should be expanded to relax the assumption that property owners have complete information about the benefits of additional information. While it is likely that property owners will be well-informed about the costs of mitigation when they decided to adopt new mitigation, it is less clear that they will know how their future losses will change. The analysis can be re-calculated under the assumption that property owners know the costs of mitigation but retain some uncertainty about the benefits of changing their behavior.

10. References

Bakkensen, L. & Mendelsohn, R.O. (2016). Risk and Adaptation: Evidence from Global Hurricane Damages and Fatalities. *Journal of the Association of Environmental and Resource Economists*, 3: 555-587.

Botzen, W. W., Kunreuther, H., Czajkowski, J., & de Moel, H. (2019). Adoption of Individual Flood Damage Mitigation Measures in New York City: An Extension of Protection Motivation Theory. *Risk Analysis*. DOI: 10.1111/risa.13318.

Emanuel, K. (2017). Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Science*, 114(48): 12681-12684.

Dixon, L., Clancy, N., Seabury, S. A., & Overton, A. (2006). The National Flood Insurance Program's Market Penetration Rate: Estimates and Policy Implications. *Report for the Federal Emergency Management Agency* (contract #282-98-0029). Santa Monica, CA: RAND Corporation.

Farrow, S., & Scott, M. (2013). Comparing multistate expected damages, option price and cumulative prospect measures for valuing flood protection. *Water Resources Research*, *49*(5), 2638-2648.

FEMA (2015). *Reducing Flood Risk to Residential Buildings That Cannot Be Elevated* (FEMA P-1037). Available at: https://www.fema.gov/media-library-data/1443014398612-a4dfc0f86711bc72434b82c4b100a677/revFEMA_HMA_Grants_4pg_2015_508.pdf

Hsiang, S. & Narita, D. (2012). Adaptation to Cyclone Risk: Evidence from the Global Cross-Section. *Climate Change Economics*: Special Issue on Adaptation, 3.

Landry, C. E. & Jahan-Parvar, M. R. (2011). "Flood Insurance Coverage in the Coastal Zone." *Journal of Risk and Insurance* 78 (2): 361– 88.

MDA Information Systems. (2016). "Analysis of Historical Satellite Imagery to Map Apparent Flood Inundation Extent". BAA Number 14-02.

Neumayer, E., Plümper, T., & Barthel, F. (2014). The political economy of natural disaster damage. Global Environmental Change, 24, 8-19.

Radiant Solutions (2018). *New Urban Flood Risk*. BAA Number 14-02.

Woodcock, C. E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., ... & Nemani, R. (2008). Free access to Landsat imagery. *Science*, *320*(5879), 1011-1011.