Benefit–Cost Analysis of Low-Cost Flood Inundation Sensors

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Abstract: The demand for inexpensive and reliable warning systems has increased in recent years as a result of the increase in the number and severity of flood disasters. A new generation of low-cost sensors for flood monitoring and warning is being developed by the federal government and private sectors, in some cases collaboratively. We perform a benefit-cost analysis of this new product category, (i.e., low-cost flood inundation sensors), which can readily be deployed in a wireless or internet of things network. The use of these sensors can improve the coverage and lengthen the lead time of flood warning systems. The production costs of this new technology are only a fraction of those of existing sensors with similar capability and reliability, and operating costs are modest. Benefits depend on such factors as the ability to improve lead times of warnings to reduce property damage, deaths, and injuries from floods as well as the extent of adoption of the new sensors. Our analysis indicates a benefit–cost ratio of 1.4 to 1. However, our results are based on several assumptions. Hence, we have undertaken extensive sensitivity analyses to determine that our results are robust. **DOI: 10.1061/(ASCE)NH.1527-6996.0000596.**

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Introduction

Floods have caused substantial damage in the United States, resulting in an average of over 100 fatalities per year over the last decade (NWS 2022) and an average annual economic loss of $7–$8 billion over the past three decades (Lightbody 2017; DHS S&T 2018; Davenport et al. 2020). Despite increased investment in flood control and warning systems, the combination of more frequent and intense extreme storm events (Dodman et al. 2022), sea-level rise, changes in land use, and a buildup of the number of assets at risk has resulted in an increasing trend of economic losses from floods. The expected damages from storm-related flooding in the United States could exceed $20 billion annually in the near future, nearly 75% of which would occur in the residential sector (CBO 2019), with prospects that losses could reach over $40 billion annually by 2050 (Wing et al. 2022). The demand for inexpensive and reliable warning systems has increased in recent years due to these various factors.

A new generation of low-cost flood sensors, which can improve coverage and lengthen the lead time of flood warning systems, is being developed by the federal government and the private sector. The data reported by such sensors are precise enough to produce prediction accuracies within the margin of error desired for public safety response and flood risk outreach efforts. Potential adopters include local governments in flood-prone communities and the private sector, including users who are already purchasing flood sensors at a higher cost or lower quality/effectiveness and those who previously had not adopted such technology.

The purpose of this paper is to perform a benefit–cost analysis (BCA) of low-cost flood inundation sensors. Benefits depend on such factors as the ability to improve lead times of warnings to reduce property damage and deaths from floods as well as the extent of adoption of the new sensors. For communities that already have an existing system of flood sensors, it is assumed that the low-cost sensors will primarily complement their existing sensor network to fill in data gaps. Due to the affordability of the new sensors relative to higher-cost sensors, communities can use them to provide more coverage and enhance their situational awareness and communication capabilities with the public. When the existing (high-cost) sensors reach the end of their useful life, it is expected that the low-cost sensors will replace them. For communities that have not established a flood sensor monitoring and warning system, it is assumed that a small portion of them will select the low-cost sensor technology in the next 10 years because of its attractiveness. Our analysis is based on data collected from the literature, information obtained from manufacturers of sensors, and insights provided by flood management practitioners and other domain experts. A number of assumptions are also adopted; hence, we have undertaken extensive sensitivity analyses to determine that our results are robust.

Many researchers have estimated the benefits of improved warning times, but these studies are mainly limited to physical property damage rather than dollar value. Moreover, 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

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allowing potential victims to seek shelter (Jonkman and Vrijling 2008), only Penning-Rowsell et al. (2005) have quantified that effect or its relationship to lead warning time. Our study contributes to the literature in a number of ways:

1. It offers a methodology for relating improvements in the lead times of flood warning systems to reductions in property damage and casualties measured in dollar values.
2. It can serve as a template for how to perform a thorough BCA of a new flood risk reduction technology in terms of assessing several types of benefits and costs and factoring in issues of adoption. Also, BCAs of new technologies of this type are rarely this comprehensive.
3. Application of our methodology will help communities make better decisions on the adoption of sensors. It is not sufficient to know that a new technology has a BCR greater than one, since any new technology must compete with others; therefore, a ranking of alternatives is usually undertaken, which requires numerical estimates.
4. Some of the development and adoption of new flood risk reduction technologies and products are supported by government funding, and there are competing areas that need government funding support. Estimation of return on investment of competing projects provides valuable information to prioritize the investment.

Baseline Analysis

Low-cost flood sensor systems are differentiated in three ways from higher-cost sensors: 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). These scientific-grade sensors have a precision level of ± 0.01 ft and cost approximately \$20,000 per unit (R. Lotspeich, personal communication, 2021). Engineering-grade sensors with precision level of about ± 0.1 ft are currently available for around \$6,000.

In contrast, the low-cost sensors considered in this study are precise enough to produce predictions within the margin of error desired for public safety response and flood risk outreach efforts at a fraction of the cost. Low-cost systems make use of the rapid pace of technological development to deliver reliable sensing capability with lower equipment, operating, and maintenance costs. These devices generally do not rely on electrical grids for power and make use of existing wireless 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 (Al Qundus et al. 2020; Andersson and Hossain 2015; Azid et al. 2015; Mao et al. 2019; Moreno et al. 2019; Mousa et al. 2015, 2016). Low-cost flood sensor systems would therefore be attractive to communities that face a 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 by such systems at a low cost. Typically, sensors use the low end of the bandwidth spectrum (2G/3G), a type of cellular service that covers most of the United States. Even in communities with limited cellular network reception, sensors can transmit and/or receive data using alternatives such as radio (e.g., ALERT2 Radio, SCADA modem, and LoRaWAN), satellite transmission, or a mesh network, which transmits data from sensor to sensor back to a network connected device.

Commercial viability is likely to be enhanced by the fact that municipal and state government agencies are eligible for various types of federal assistance, including pre- and postdisaster funding from the Federal Emergency Management Agency (FEMA) through its public assistance and hazard mitigation grant programs for purchasing flood sensors. Further adoption by the private sector is also likely, with expressions of interest already tendered from security firms and retailers in the United States and other countries (J. Booth, personal communication, 2019).

Cost Analysis

We consider five types of costs: research and development (R&D); product; installation; operation; and data management.

Government agencies and the firms producing the flood sensors incur R&D costs. For the latter, we assume that the private sector R&D costs are factored into the selling price of the products. For government costs, we estimate the cost of the flood inundation sensor program, an initiative of the US Department of Homeland Security Science and Technology Directorate's flood apex program that sought to spur private sector development of low-cost sensors. The public sector R&D costs amount to \$6.74 million, which include potential research, development, and transition costs for such projects as identified in a BCA methodology for DHS-related research projects (2017 dollars) (von Winterfeldt et al. 2019). A description of the flood inundation sensor program and a breakdown of costs are available in Appendix I.

Product, installation, operation, and data management costs are based on the average of 11 bids that companies submitted to Hampton Roads Planning District Commission in Virginia to establish a network of 20 low-cost sensors. We consulted flood management practitioners involved in sensor procurement to confirm our estimates are plausible (C. Kirby, personal communication, 2021; R. Lotspeich, personal communication, 2021). The cost estimates are:

- Product costs. This pertains to the sales price of the low-cost sensor product based on the unit price data quoted in the bids mentioned above, which is estimated to be \$2,000 per unit. This is an average of the price of several bids, excluding bids where product costs were aggregated with other cost categories, and was confirmed as a reasonable estimate by a sensor manufacturer representative (R. Guerrero, personal communication, 2021).
- Installation costs. These amount to \$1,000 per sensor. The installation of the sensors is relatively simple because the sensors can be tied to telephone poles or bridge components.
- Operation costs. These sensors are operated using battery and solar charging; therefore, their operating costs are smaller than those for other sensors. The battery maintenance cycle can range from one to 10 years. We estimate costs of \$800 per sensor per year, including internet connectivity.
- Data management. The input of sensors typically needs to be integrated into a data platform to allow for real-time monitoring. Where the user already has a sensor network in place and simply needs to integrate the new sensors into the existing platform, we estimate first-year costs of \$12,500 and \$3,000/year thereafter. In cases where the user does not have an existing sensor

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Table 1. Product and installation costs of low-cost flood inundation sensors (2017$)

Unit	Product cost	Installation cost	Operation cost	Data platform setup	Data platform maintenance
Individual sensor	$2,000	$1,000	$800/year	—	—
Sensor network	—	—	—	$12,500–$37,000	$3,000/year–$9,000/year

network, we assume first-year costs of $37,000 and ongoing costs of $9,000/year. These costs include programming costs, software licenses, and staff training.

Individual product, installation, operation, and data management costs are presented in Table 1. Note that the cost of adopting and implementing the low-cost flood sensors dwarfs public sector R&D costs.

Benefit Analysis

Overview

Lower-cost sensors can yield benefits through the implementation of flood inundation monitoring in three ways:

1. Improvement in lead warning time 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.
2. Wider adoption of flood sensors. This applies to new users attracted by the products' enhanced ability to improve warning systems. 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 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 new generation of internet of things (IoT) sensors can be compared with other alternative products available in the current market that have similar capabilities. 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 $2,000 per unit, much less expensive than many flood sensors in use today. We evaluate these potential cost-savings, which are added to the benefits side of the ledger.

Methodology

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, which potentially stem from several sources caused by flooding in general, though with varying relevance to the case in point. The most difficult aspect of this analysis is linking improved warning time and accuracy to the implementation of protective and relocation measures.

Table 2 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.

Many researchers have estimated the benefits of improved warning times, but these studies are mainly limited to physical property damage rather than dollar value (see Appendix II for a summary of the literature). Moreover, nearly all studies to date have not estimated the separate effects of all the various protective measures that can reduce losses. Nor have they included all relevant measures; thus, even the use of an aggregate estimate, which is all that would be required for our study, would have limitations before noting still others. For example, many of these estimates are performed for specific types of flooding (such as coastal areas subject to flood surge) or noncomparable countries (foreign countries with much different building stocks). These characteristics make the use of these results on our part somewhat tenuous.

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 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.

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 and Vrijling 2008), few studies have quantified that effect or its relationship to lead warning time. Nevertheless, those studies suggest that improved warning systems have a modest effect on reducing casualties, and they are useful in providing an

Table 2. Benefits of enhanced flood warning

Protective measure mechanisms	Potential	Mechanism	Cost	Scope (obstacle)
Protect physical assets (PD, BI)	Moderate	Temporary barriers; community measures	Low	Low (time)
Relocate physical assets (PD, BI)	Low	Mobility; high value contents	Moderate	Low (fixed in place)
Relocate production (BI)	Moderate	Branch plants/offices	Low	Low (subset of firms)
Protect people (VOSL)	Moderate	Temp barriers; elevate	Low	Low (time)
Relocate people (VOSL; BI)	Significant	Evacuation	High	Significant (congestion)

Note: PD = property damage; BI = business interruption; and VOSL = value of statistical life.

upper bound on our assumptions about the relationship between warning time and mortality and morbidity.

Benefit estimation for low-cost flood sensors. We avoid relying on estimates from the literature that are ill-suited to this context by implementing a "direct estimation" approach. The benefits of warnings associated with low-cost flood sensors are calculated based on the following data:

1. current flood warning times;
2. flood (property) damage and loss (of life and business) with current flood protection tactics and flood warning techniques;
3. flood warning improvements
   - improved warnings (including lead time);
   - lower-cost warnings; and
4. flood damage and loss reduction with tactics implemented in response to changes in warnings.

For the last bullet point, we note that it is preferable to subtract out the cost of implementing the flood risk reduction tactics, though data were not available to do so in our case. The reader is referred to Dormady et al. (2022) for an example of the latest work on this under-researched topic.

We implement the following set of result/calculations:

1. Access data on current average warnings times. Improvements refer to increased warning time. 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 are evaluated separately. Therefore, we defer discussion of the deployment of an increased number of sensors to a later section on technology adoption.
2. Access data on flood damage/loss with current warning systems for the United States as a whole.
3. 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.

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 USGS, supplemented by weather radar and hydrological models. We use the National Weather Service's (2011) typical lead times records for flood 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, as reported by the National Oceanic and Atmospheric Administration (NOAA) storm events database (2019). Data on flood-related damages are based on the mean of the following three estimates: (1) average damages reported by the storm events database from 2004 to 2018 ($9.3 billion); (2) 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 (3) 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% based on the average of two projections by Wing et al. (2018) for expected damages. That figure is derived by first estimating the increase in expected damages by 2025, assuming a linear annual increase in damages. Expected damage is estimated to increase from 2017 to 2025 by 9.2% or 13.82%, depending on population growth and migration scenarios. We use the average of those two projections (11.51%) 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 (often referred to as "pathways"), 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 (i.e., forecast accuracy, the translation of forecasts into warnings, or alerts, 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 complexity of the decision process (see, e.g., Pappenberger et al. 2015). 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.

Relationship between warning time and damage reductions: We estimate the improvement in warning time resulting from the implementation of new sensors based on the "day curve," which relates warning lead times (in hours) to percentage property damage prevented. 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). Fig. 1 presents the original day curve cited in the HAZUS Flood Model Technical Manual. It assumed a 100% public response rate and a maximum loss reduction rate of 35% to both structure and contents. In our estimation, we cap the public response rate at 85%, as suggested by the New York District of USACE (1994).

Benefits of lower-cost sensors: Gains to consumers also arise from the availability of lower-cost flood sensors. The USGS uses scientific-grade sensors, primarily for research purposes with a precision level of ± 0.01 ft, which cost approximately $20,000 per unit. Engineering-grade sensors with a precision level of about ± 0.1 ft are currently available for around $6,000. The low-cost sensors are comparable to engineering-grade sensors but not replacements for the more precise scientific-grade sensors. The low-cost sensors will likely compete with engineering-grade sensors, but their adoption is unlikely to negatively affect flood loss

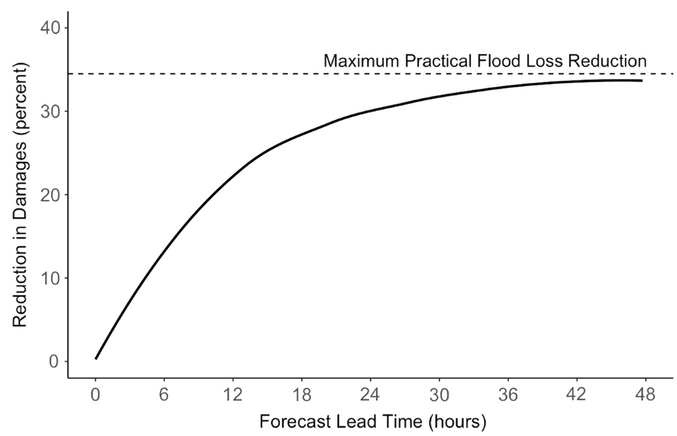

Fig. 1. Day curve. (Adapted from FEMA 2013.)

reduction. While the low-cost sensors are less accurate, their measurements are sufficient for the purpose of modeling and predicting floods. We do not expect the low-cost sensors to compete with the much more expensive scientific-grade sensors the USGS and other federal agencies employ, as those agencies require a higher degree of accuracy, reliability, and connectivity. Therefore, the new low-cost sensors are not expected to replace those scientific-grade sensors but rather are more likely to be adopted to complement those sensors. Thus, we estimate potential per unit savings of $4,000 from their availability. Because not all additional and potential users will adopt the sensors because of the lower price, we use a rule of thumb determined by von Winterfeldt et al. (2019) of utilizing only one-half of the potential savings.

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 to a broader set of owners of structures who are concerned about flood damage. Insurance firms see sensors as a way to reduce payments for flood losses and are likely to incentivize their adoption. Security firms such as ADT have also 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 (J. Booth, personal communication, 2019). We explore several options, some noted in the following, and also consider using a reasonable range of upper- and lower-bound adoption scenarios. FEMA (2019) provides a data visualization tool based on NOAA storm event database data, which indicates that 98% of all US counties or equivalents, roughly 3,080 counties, were impacted by at least one flooding event between 1996 and 2016. We estimate adoption of low-cost sensors for improved monitoring based on whether a county has received a StormReady certification from the National Weather Service (NWS). As of July 15, 2020, the NWS reported that 1,490 of the 3,242 counties and county-equivalent bodies are StormReady certified (NWS 2020). To obtain the certification, counties must meet certain conditions, including having a system that monitors weather conditions locally and operating a 24 h warning point and emergency operations center (NWS 2017). We assume that adoption will be much higher among the StormReady-certified counties.

Table 3 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 lower-cost sensors in a 10-year horizon.

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%. We conclude that an improvement in lead warning time will likely reduce casualties by a lower amount since most communities in the United States already have an adequate warning system but use the 6.5% 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:
   a. Loss of life prevention
      (1) Lower-bound: 2 (2.5% reduction);
      (2) Base case: 4 (4%); and
      (3) Upper-bound: 6 (6.5%).
   b. Injuries prevention
      (1) Lower-bound: 2 (2.5%);
      (2) Base case: 3 (4%); and
      (3) Upper-bound: 5 (6.5%).

   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 (i.e., equivalent to a concussion or major abrasion) and that the cost of such an injury is 4.7% 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 to community-wide measures such as stream diversion and emptying 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 "Benefit Analysis" section.

   The major assumptions involved are
   a. Adoption of low-cost sensors
      Case A: Communities or users that already employ warning systems.
      A1. The new-generation sensors can help improve lead warning time. Therefore, the new sensor system will be established to complement the existing warning systems.

Table 3. Assumptions for key variables affecting adoption of low-cost sensors

Variable	Lower-bound	Base case	Upper-bound
A. Number of years of product life	3	5	8
B. Number of NWS certified counties/parishes	1,490	1,490	1,490
C. Number of non-NWS certified counties/parishes	1,752	1,752	1,752
D. Percentage of NWS certified counties likely to adopt	70%	80%	90%
E. Percentage of non-NWS certified counties potentially adopt	10%	20%	30%
F. Number of communities and businesses within each county that purchase the sensors	2	3	4
G. Number of sensors per customer	25	50	75
H. Number of customers [$= (B \times D + C \times E) \times F$]	2,436	4,627	7,466
I. Number sensors needed [$= H \times G \times (\frac{10}{A})$]	203,033	462,720	699,975

Note: Rows A through G are assumptions; and Rows H and I are the calculation results.

Table 4. Cost savings of low-cost sensors

Case	Per unit: Engineering-grade IoT sensor price	Low-cost IoT sensor price	Cost saving	Adjusted cost saving	Total: # of sensors	Total cost savings
Case A	$6,000	$2,000	$4,000	$4,000	357,600	$1,430,400,000
Case B	$6,000	$2,000	$4,000	$2,000[a]	105,120	$210,240,000
Total					462,720	$1,640,640,000

[a]Because not all potential users without an existing system network (Case B) will adopt the sensors because of the lower price, we use a rule of thumb determined by von Winterfeldt et al. (2019) of utilizing only one-half of the potential savings.

A2. The new-generation sensors are of lower costs. Therefore, when the existing sensors reach their useful life, the current users will choose the new sensors to replace the existing technology.

Case B: Communities or users that currently do not have any warning system in place.

B1. New users can be attracted by the products' capacity to provide lead warning time of flooding hazards, thus leading to wider adoption of flood sensors in counties that currently have not adopted the warning system.

B2. New users can also be attracted by the lower cost of these products relative to those already in the market.

Based on our consultation with flood management practitioners, for Case A, we assume that 80% of the NWS-certified counties will adopt the new sensor. For Case B, we assume that additional adoption will take place in 20% of the noncertified counties (Kirby 2021; R. Lotspeich, personal communication, 2021).

b. Average current warning time

Case A: NWS-certified counties: 9 h.

Case B: Non-NWS-certified counties (entities are dependent on long-distance warning): 6 h.

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

- Lower-bound: 10%.
- Base case: 25%.
- Upper-bound: 40%.

3. Cost savings: Table 4 presents the calculations for the cost-savings. 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 who do not currently have a sensor network are considered to benefit from only half of the cost-savings, as previously explained. The total cost savings over the life of the sensors amount to more than $1.6 billion.

The 9 h 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 h by the National Weather Service (NWS 2011). The 6 h average current warning time assumed in Case B is derived by using the minimum for the range of lead times for flood warnings.

Application of the day curve indicates that a 9 h warning time can reduce damages by 16.81% (applying an 85% response rate to flood warnings). This figure is lower than the lower-bound in the literature of approximately 35% (see, e.g., Pappenberger 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 aforementioned assumptions results in the values that are inputs into our estimation process as presented in Table 5. Note that there can also be benefits associated with evacuations, which include two major types: more evacuations and fewer false positive evacuations. Note that estimates of evacuation benefits are not included in the analysis at this time. However,

Table 5. Property damage reduction assumptions and estimated levels

Property damage reduction	Lower-bound (%)	Base case (%)	Upper-bound (%)
Existing local warning systems (Case A)			
Improved lead times	10	25	40
New damage reduction levels	17.56	18.57	19.47
Improved reduction	0.75	1.76	2.66
New local warning systems (Case B)			
Improved lead times	65	87.5	110
New damage reduction levels	17.56	18.57	19.47
Improved reduction	3.96	4.96	5.86

it is safe to say that they would not increase our benefit estimates by more than 10%, and likely much less.

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 in Case A and Case B communities to estimate the benefits of adoption of the low-cost flood sensors in the base case (presented in Table 6). Note that total costs include the R&D costs, installation/maintenance cost of sensors, and cost of data response platform. Total benefits include life safety and reduction in property damage. Over the 10-year analysis period, the discounted total benefits and costs in the base case are estimated to be $2.23 billion and $1.59 billion, respectively. These yield a BCR of 1.4 and a rate of return on investment of 40.4%. The benefits will likely vary for different geographic regions based on vulnerability to flooding, population size, and land use. For example, major population centers along the coast that are susceptible to hurricanes and nor' easters would likely experience a higher BCR than rural, in-land communities. The benefits may also be larger for areas that experience flash floods, which are less predictable than storm surge events.

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 BCR (in excess of 50:1).

Sensitivity and Uncertainty Analysis

A sensitivity analysis was undertaken using the base case, lower-bound, and upper-bound values of variables summarized in Table 7 and based on the discussion in previous sections.

The major assumptions made in our analysis are listed below (in the sequence low, medium, high):

- Total DHS program cost: $6.74 million; and
- Per-unit sensor cost: $1,000, $2,000, $3,500.

Table 6. Base case analysis of the benefits of flood sensors

Variable	Base case
Public sector R&D costs	6,739,546
Equipment cost per sensor	2,000
Number of sensors needed	462,720
Total equipment cost of sensors[a]	925,440,000
Installation cost per sensor	1,000
Total installation cost of sensors[b]	283,920,000
Operation and maintenance cost (per sensor per year)	800
Total O&M cost[c]	583,187,027
Setup cost of response platform per system (first year): new system	37,000
Setup cost of response platform per system (first year): existing system	12,500
Maintenance cost of response platform per system per year: new system	9,000
Maintenance cost of response platform per system per year: existing system	3,000
Number of systems need new response platform[d]	788
Number of systems integrating to existing platform[e]	2,051
Total initial setup cost of response platform	54,805,800
Total maintenance cost of response platform[f]	54,782,270
Average annual property damages caused by floods in baseline	13,100,000,000
Projected average annual increase of baseline property damages by floods (percentage)	1.57
Increased percentage of avoided property damage from improved lead time	1.76
Increased percentage of avoided property damage from more coverage	4.96
Benefit of reduced property damage from improved lead time in year 10	99,198,111
Benefit of reduced property damage from more coverage in year 10	82,146,159
Total benefit of reduced property damage in year 10	181,344,270
Reduction in cost per sensor (comparing to other effective IoT sensors)	4,000
Benefit from cost savings in year 10	177,366,486
Benefit of life safety in year 10	40,000,000
Benefit of reduced injuries in year 10	141,000
Discount rate (percentage)	3
Ten-year discounted benefits[g]	2,231,006,401
Ten-year net benefits[h]	642,137,439

[a]Calculated by multiplying equipment cost per sensor by total number of sensors needed.
[b]Calculated by multiplying installation cost per sensor by total number of sensors in Case A1 and Case B. For Case A2, because the new low-cost sensors are to replace the existing sensors when they reach end of useful life, it is assumed that there is no increased installation cost compared to the case that old-generation sensors are used for the replacement.
[c]Net present value (NPV) of annual O&M costs of the sensors over the 10-year study period.
[d]Assume that 75% of communities in Case B need the establishment of new response platform.
[e]Because in Case A1, the new sensor system will be established to complement the existing warning systems, it is assumed that all sensors in Case A1 can be integrated into existing response platform.
[f]NPV of annual O&M costs of the response platforms over the 10-year study period.
[g]NPV of total benefits (including cost savings from adopting low-cost sensors, avoided property damages, and avoided deaths and injuries from flooding) over the 10-year study period.
[h]Calculated by subtracting NPV of sensor equipment costs, response platform costs, and public sector R&D costs from the NPV of total benefits.

Table 7. Ranges of variable values for flood sensors

Input variables	Low	Base	High
Equipment cost per low-cost sensor	1,000	2,000	3,500
Equipment cost per other effective IoT sensor	5,000	6,000	8,000
Installation cost per sensor	500	1,000	1,400
Cost of response platform per system (first year): new system	23,000	37,000	48,000
Cost of response platform per system (first year): existing system	7,800	12,500	16,200
O&M cost of sensors	400	800	1,200
Maintenance cost of response platform (new)	7,000	9,000	12,000
Maintenance cost of response platform (existing)	2,400	3,000	4,100
Percentage of NWS certified counties likely to adopt (Case A)	70	80	90
Percentage of sensors in case a used to supplement existing warning system	25	50	75
Percentage of non-NWS certified counties/parishes likely to adopt (Case B)	10	20	30
Number of communities/businesses within each county that purchases the sensors	2	3	4
Projected average annual increase of baseline property damages by floods (percentage)	1.27	1.57	1.87
Improved reduction in property damage from improved lead time (percentage)	0.8	1.8	2.7
Improved reduction in property damage from more coverage (percentage)	4.0	5.0	5.9
Product life (in years)	3	5	8
Number of sensors purchased per customer	25	50	75
Annual life savings in year 10	2	4	6
Annual reduced injuries in year 10	2	3	5
Discount rate	0	0	0

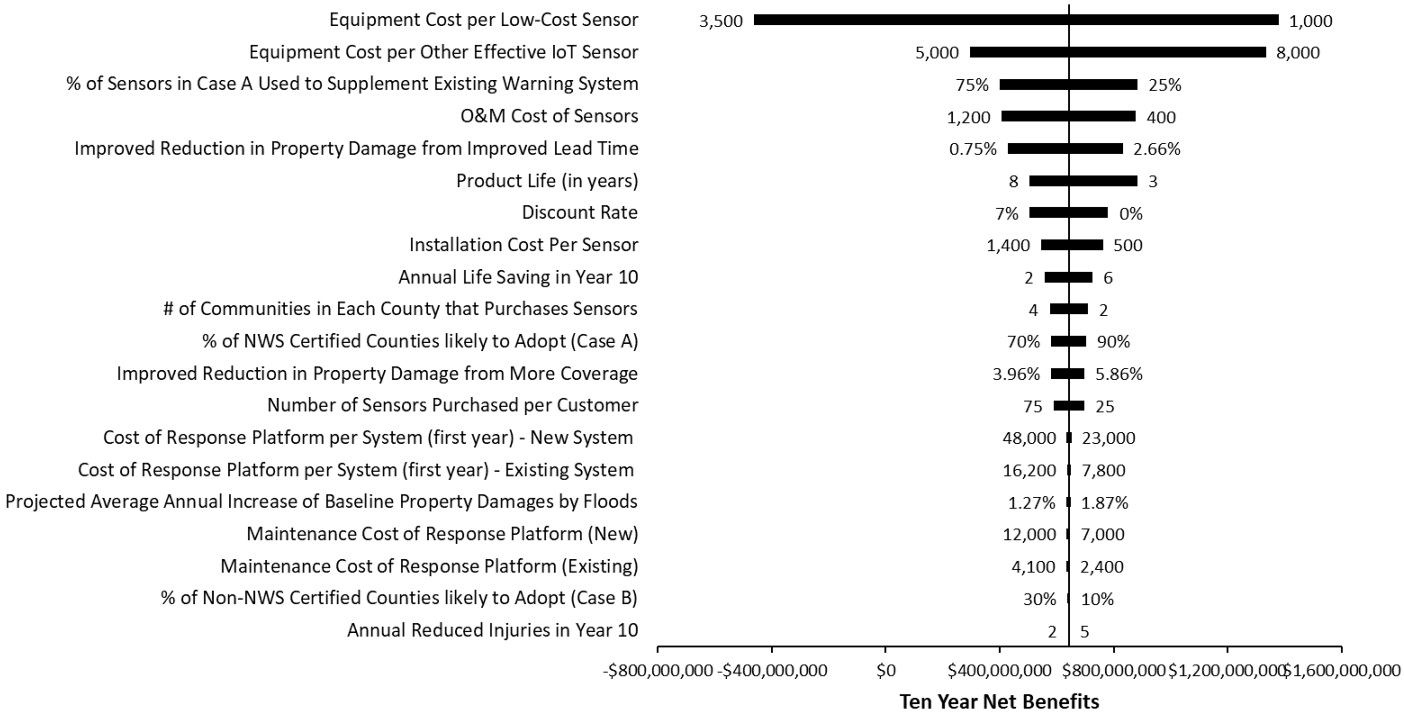

Fig. 2. Tornado diagram for 10-year net benefits of flood sensors.

Benefit estimation:

- Average current warning time: 9 h for Case A and 6 h for Case B; and
- Improvements in warning time (Case A and Case B): 10%, 25%, 40%.

Technology adoption:

- Number of years of product life: 3, 5, 8;
- Number of additional counties adopting: 175, 350, 526;
- Number of communities/large businesses within each county that purchases the sensors: 2, 3, 4; and
- Number of sensors per customer: 25, 50, 75.

The estimated net benefits associated with the low-cost sensors are especially sensitive to some of the assumed parameters, primarily on the cost side. Fig. 2 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 parameters most sensitive to changes are those with the longest bars in the diagram. The sensitivity analysis indicates that the largest uncertainty comes from the assumptions around the cost of the new flood sensors compared to the cost of the existing IoT sensors in the market they displace. Other important variables include the proportion of new sensors being used to supplement existing warning system versus replacing the existing sensors, annual O&M cost, and expected reduction in property damage because of the improved lead time.

To explore the uncertainty associated with the estimates of the 10-year net benefits, we conducted a Monte Carlo simulation. We assumed triangular probability distributions for all variables listed in Table 7, 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 Fig. 3. The 5th, 50th, and 95th percentiles, as well as the mean and median of the distribution, are presented in Table 8. The uncertainty analyses on these variables indicate a median net benefit of $408.3 million, with a fifth percentile of −$211.5 million and a 95th percentile of $834.6 million.

We also conducted a separate sensitivity analysis on the period of analysis for the base case. When the analysis period is reduced to 5 years, the BCR is reduced from 1.40 to 1.35. The BCR is estimated to increase to 1.44 when the analysis period is extended to 15 years. In general, the BCR slightly increases as the period of analysis is extended, because more net benefits from adopting the low-cost sensors can be achieved during a longer term.

Limitations and Additional Research

The main limitations of this analysis relate to the estimation of benefits. We do not consider benefits resulting from the improved accuracy of warnings or the reduction in business-interruption costs. Furthermore, in using the original day curve to estimate property loss aversion, our estimation caps public compliance to flood warnings at 85%, but we do not implement other modifications that have been suggested in the literature that require more data than were available to us. These modifications include considering the specific relationship between building locations and forecast lead time, incorporating the average speed of warning dissemination, and accounting for the differences in residential structures since 1970s (USACE 1994; Carsell et al. 2004). Finally, the analysis does not consider how different climate change scenarios would affect benefit estimates. However, since projections of flood damage have increased greatly, partly due to climate change causing more frequent and severe storm events (Dodman et al. 2022; Wing et al. 2022), the benefits of the adoption of low-cost sensors are likely to increase due to climate change.

The analysis does not consider distributional impacts, but the low-cost sensors have the potential to reduce existing inequalities

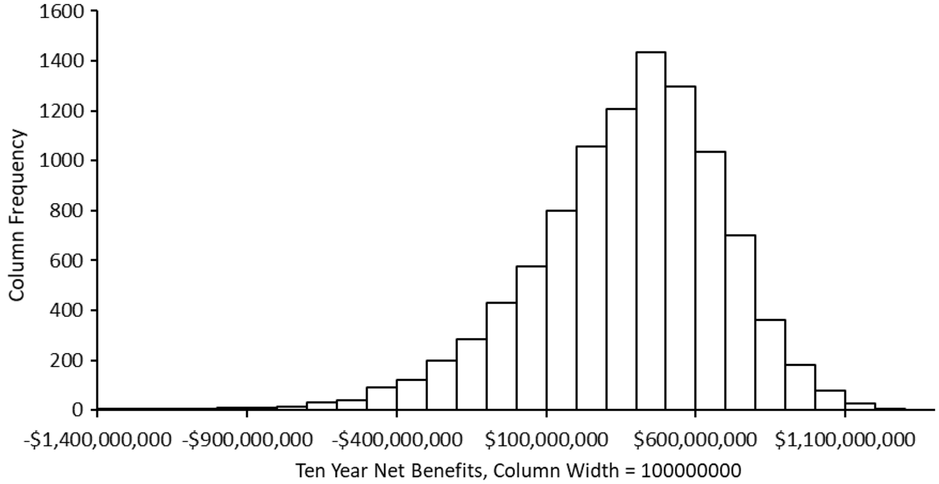

Fig. 3. Distribution of 10-year net benefits of flood sensors.

Table 8. Statistics of the net benefits distribution

Statistical measure	Value
Mean	\$370,976,498
Standard deviation	\$320,688,124
5th percentile	−\$211,533,110
25th percentile	\$188,122,993
Median	\$408,296,425
75th percentile	\$590,628,756
95th percentile	\$834,610,124

in flood monitoring among at-risk communities. The high cost of other sensors and the lack of connectivity in some areas are barriers to adoption for communities and users that currently do not have any warning system in place (Case B). The low-cost sensors improve affordability and offer more connectivity options and thus are likely to reduce the gap in flood monitoring capabilities among at-risk communities. Adoption could be further increased through subsidies such as FEMA's Hazard Mitigation and Flood Mitigation Assistance programs. Greater access to flood monitoring systems has important equity considerations, as annual flood losses are disproportionally borne by poorer communities, and as future increases in flood risk are projected to disproportionally impact black communities (Wing et al. 2022). 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. More research on market penetration of the new sensors and the communities' awareness of the 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 deployment of the new sensors can increase the warning time of any existing warning systems by 25% 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. Future research can also examine how the benefits of these sensors vary for different communities based on flood-affecting conditions as well as social, demographic, and economic factors.
5. The increase in warning time associated with the adoption of the sensors also help to avert economic losses other than the direct cost of property damage. Some of those flood cost types, most notably business interruption (BI), have ripple, or multiplier, effects on both economic output and employment throughout the area affected by the flood and beyond (Rose 2004). In a small set of cases, those costs can be larger than property damage. The ability to reduce BI via the use of sensors is much lower than for structural floodproofing measures and land-use planning strategies, however, because sensors do not prevent floodwaters from damaging or interrupting businesses. Note also that BI associated with evacuation, as well as imputed costs to households (Rose and Oladosu 2008), can be significant but is typically offset to a great extent by recapturing lost production upon return (Rose 2017). Many of these broader flood losses that can be potentially mitigated because of the adoption of the new sensors should be addressed in future studies. For now, their omission suggests that our results may be considered a lower bound of benefit estimates.

Conclusion

This paper has applied a state-of-the-art benefit–cost analysis approach to the evaluation of the net benefits and rate of return on investment of low-cost, modern flood inundation sensors developed as part of public and private sector research. This new sensor design can be deployed in an IoT configuration and promises lower costs and improved accuracy.

The research involved identifying key aspects of both the benefit and cost sides of the ledger. It was necessary to invoke several important assumptions given the fact that we are making projections about future considerations such as production costs at full-scale operation and technology adoption. Accordingly, we undertook a comprehensive sensitivity analysis to ensure that our results were robust.

The major findings of the paper include

- Calculation of a base case BCR of 1.4 and a rate of return on investment of 40.4%;
- Cost savings relative to more expensive sensors make up a significant part of the benefits; in year 10, those cost savings amount to $177M, over and above $168M from property damage averted;
- Our estimates are especially sensitive to changes in the cost of the sensors and the savings relative to the more expensive sensors;
- Public sector research and development costs are minor compared to overall costs and to the market potential of these products; and
- Our benefits estimates are conservative because we did not include BI costs savings or factor in some benefits (such as reduced false positive alarms) from more accurate warnings.

The study contributes to the evaluation of new technologies of flood risk reduction in several ways. First, it can serve as a template for performing a thorough BCA for any such new technology based on the evaluation of several major categories of benefits and costs. It also offers a methodology linking improvements in flood warning lead times and reductions in property damages and casualties. Application of the methodology developed in this study can help communities make better decisions on the choice of alternative risk-reduction technologies based on the ranking of estimated BCRs. Finally, in cases where government R&D funding is provided, estimation of return on investment of competing projects can provide valuable information for the government funding agencies to prioritize investments.

Appendix I. Parameters for Research and Development Costs and Literature Synthesis of Flood Warning Studies

The US Department of Homeland Security Science and Technology Directorate (DHS S&T), in conjunction with the Federal Emergency Management Agency (FEMA) and the Small Business Administration (SBA), has established the flood apex program to reduce losses from flooding. One of the products to which its research and development efforts have been applied is a low-cost flood inundation sensor that can readily be deployed in a wireless or IoT network.

The flood inundation sensor program consisted 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. 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 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., received $750,000 to produce a prototype. The beta testing involved distributing sensors to 300 stakeholders for field testing (J. Booth, personal communication, 2019).

Phase 3, which extended from July 26, 2019, to July 25, 2021, focused on product commercialization with the intent of being able to produce 250 to 1,000 sensors per week. At the outset, the federal government paid for testing and evaluation.

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 semifinalist firms; and
- $0.72 million to Intellisense.

Oversight and transition development costs: $2 million.

Appendix II. Literature Synthesis of Flood Warning Studies

Study	Location	Warning system or technology	Annual cost	Damages prevented: Methods	Damages prevented: Pathways	Damages prevented: 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 nonprimary measures on risk reduction"	—	—	—	—
DHS S&T (2017)	—	Smart Alerts Pilot Project	—	—	—	—	—	—
Loftis et al. (2018)	Hampton Roads, Virginia	Stormsense	$3,000/sensor $4,400/radar unit	—	—	Sensor accuracy: ±5 mm ±18 mm	—	—
Molinari and Handmer (2011)	—	—	—	Behavioral model using event tree	—	—	—	—

Appendix II. (*Continued.*)

Study	Location	Warning system or technology	Annual cost	Damages prevented: Methods	Pathways	Estimates[a]		BCRs	Comments
Moreno et al. (2019)	Colima, Mexico	RiverCore	—	Message queuing telemetry transport protocol	Measures: peak-flow depth underground sound mean flow velocity surface velocity flow depth ground vibration basal forces fluid pore pressure impact force	—		—	—
Pappenberger et al. (2015)	Europe	European Flood Awareness System (EFAS)	41.8 M Euros (21.8 M for four centers; 20 M over 10 years for maintenance)	Probabilistic forecasting with standard weighted annual average damage values	Flood defenses Watercourse maintenance Community defense Moving/evacuation Warning resistance Early warning	32% 0.9% 0.36% 5.7% 0.0036% 32.85%		155:1 4:1 2:1 28:1 0.02:1 159:1	—
Priest et al. (2011)	England & Wales Grimma, Germany	No specific tech Part of floodsite project	—	Flood warning response benefit pathways (FWRBP)	— Flood defenses Watercourse maintenance Community defense Moving/evacuation Business continuity Resilience measures	England & Wales: 28% 10% 1% 5% 5% 2%	Grimma, Germany N/A 5% 1% 5.8% 6% 3%	—	—
Verkade and Werner (2011)	Scotland	Flood forecasting, warning and response systems (FFWRS)	—	Hydro-economic model of expected annual damage combined with relative economic value ("dimensionless factor" to scale between "no warning"/"perfect warning" cases)	Warning lead times	1 h: 2% 2 h: 3% 3 h: 3% 4 h: 9% 5 h: 11% 6 h: 11%		—	—

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

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request including data on cost of sensors and response platform, including installation and operating and maintenance costs, from nine companies and full dataset and results of the uncertainty analysis and the sensitivity analysis.

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