Planning for Natural Disasters in a Stochastic World

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Abstract

We examine the risks and management of natural disasters. A benefit-cost framework focuses attention on (1) designing control structures, such as dams and levees, and mitigation policies, such as construction standards, to protect lives and property against small and medium, rather than large sized natural disasters; and (2) warning and evacuation to save lives for large natural disasters. Providing information rather than command solutions generally enhances social benefits, if people understand the risks and bear the expected costs. Requiring actuarially fair insurance simultaneously provides information and has individuals bear the expected costs.

Keywords Natural disasters · Externalities · Equity · Decision making under risk and uncertainty · Climate · Benefit-cost analysis

JEL Classification D61, D62, D63, D81, Q54

1. Introduction : The Distribution of Extreme Events

Hurricanes, tornadoes, ice storms, floods, and earthquakes take hundreds of lives and cause billions of dollars of damage in the USA each year. A rational response to these events requires clear goals, knowing the frequency of natural disasters by destructive power, the alternatives and costs of protecting people and property, and how people react to the events. We begin by examining the distributions of extreme events, using floods as an example.

Extreme floods and rainfall occur more frequently than one might expect from consulting the memories of an area's residents. The distributions of the largest annual floods and rainfall have "fat" right hand tails, indicating that extreme events are more frequent than would be expected with a normal distribution (National Research Council, 1988).

Flood control dams are constructed to protect people and property, but designers recognize that the largest floods will overwhelm any dam; they seek to avoid deaths caused by the failure of a flood control structure. For "high hazard" dams, those whose failure could result in deaths, the government mandates that the dam be able to survive a "probable maximum flood" (PMF) (National Research Council, 1985). The PMF is the design basis flood derived from estimates of the likely maximum precipitation and runoff for each location; it has increased over time, resulting in costly retrofits of some dams.

Ensuring that a dam can survive a PMF does not mean that it will protect people and property downstream. A flood control dam is designed to impound storm waters up to a specified size. Larger storms, although rare, are spilled, flood those downstream. Without an adequate spillway, the flood water of a larger storm would overtop the dam, possibly destroying it or even causing a catastrophic failure that released a wall of water destroying the lives and property of those downstream.

Suppose that a particular dam could contain a 50-year flood (it would spill a larger flood), but the capacity of the spillway meant that it would fail catastrophically if a 100-year or larger flood occurred. Assume that funds were available that could either enable the dam to contain a larger flood (and fail, possibly catastrophically, if a 101 year flood occurred) or the funds could enlarge the spillway so that the dam would not fail if a 1,000 year flood occurred. To decide the better use of the funds, we need to compare the present discounted values of the flooding losses from a larger dam (with less frequent flooding but some chance of catastrophic failure) with the present discounted losses from the existing dam but with less chance of catastrophic failure.

At present, US policy is to use the available funds to enlarge the spillway to pass a PMF. No analysis is done to estimate whether society would get more benefit from enlarging the dam rather than enlarging the spillway. The current policy seems to indicate that dam designers and owners are focused on the ethical and legal liabilities from having their dam fail, resulting in death and destroyed property in the flood plain. The insistence on a spillway that can handle the largest plausible storm is a way of eliminating that liability, although it does nothing to protect people against flooding from smaller storms.

1.1 Calculating the sizes of a dam and spillway

The benefit of a dam depends on:
w, the size of flood, measured in cubic meters/sec
T(w), the return period for a flood of size w – measured in years
L(w), the loss from a flood of size w
D(w), the cost of building a dam that can impound a flood of size w
S(w), the cost of building a spillway that can handle a flood of size w and
i, the social rate of discount.

Assume that a dam is built that can impound a flood of size x and a spillway is built that can handle a flood of size y without harming the dam. As derived in the appendix, optimizing size of the dam gives first order condition:

$$\frac{dD}{dx} = \frac{L(x)}{(1+i)^{T(x)}} \qquad (1)$$

This first order condition tells us to increase the size (impoundment capacity) of the dam until the additional cost of another unit of expansion is equal to the present discounted loss of flood prevented by the dam expansion.

The first order condition for the size of the spillway is:

$$\frac{dS}{dy} = \frac{-L(y)^{*}}{(1+i)^{T(y)}} + \frac{L(y)^{**}}{(1+i)^{T(y)}} = 0 \qquad (2)$$

Where L(y)* is the loss from flooding from a storm of size y that is spilled over the spillway and L(y)** is the loss from flooding from a storm of size y that causes catastrophic failure of the dam. This first order condition tells us to increase the size of the spillway (the ability to protect the dam from catastrophic failure) until the additional cost of another unit of expansion is equal to the present discounted loss due to the additional loss from catastrophic dam failure.

We can characterize these functions: dD/dx and dS/dy are positive and have positive second derivatives: It becomes increasingly expensive to enlarge a dam and a spillway at a given site. dL/dw is positive and the second derivative is negative since there is only so much property to destroy.

The shape of these functions leads to choosing dam and spillway sizes that protect against a medium sized flood. There is no net benefit from protecting against the largest floods, since the costs of the dam and spillway exceed the present value of the additional flood protection.

Estimating the large flood likely to occur in an area is difficult, especially because there is rarely 100 years of data on the size of floods in an area. As shown in Table 1, the average of the largest annual floods on the Rio Grande (New Mexico) was about 150 cubic meters per second (CMS); the largest flood observed in 86 years was almost 500 CMS (Resendiz-Carrillo and Lave, 1987). Various extreme value distributions were fit to the data and used to predict the 500 year flood. Four commonly used distributions[1] fit the data equally well but gave predictions that ranged from 547 to 928 CMS. The PMF at this location on the Rio Grande is 850 CMS, 70% larger than the largest observed flood. There are insufficient data to be able to choose one distribution as superior to the others; all fit the observed data but they have quite different implications about the likelihood of large floods. can be used to evaluate the likelihood of a PMF. For this site, the distributions estimate that the return period for the PMF ranges from 350 years to 11 million years.

At the site of the Mohawk dam on the Walhonding River (Ohio), the average of the largest annual floods is about 570 CMS (Resendiz-Carrillo and Lave,1990). The largest flood observed in 66 years was 2,000 CMS. The PMF is 10,800 CMS. Thus, the PMF is only 70% larger than the largest flood observed on the Rio Grande, but is five times larger than the largest flood observed on the Walhonding. Using the four estimated distributions, the return period for the PMF ranges from 2.2 million years to 4.6 quadrillion years. Table 1 summarizes these data.

[Note to editor: table 1 should be placed at this point in the text.]

The Mohawk Dam was designed to impound a flood of 2,900 CMS, which is larger than the 500 year flood. The area downstream from this dam is sparsely populated. If the PMF occurred and the dam didn't fail, the Army Corps of Engineers estimated the spilled flood waters would cause damage of only $550,000; even if the dam failed catastrophically, the flood damage would be only $900,000. The estimated cost of retrofitting the dam so that it could pass the revised PMF (although it was constructed to pass a PMF when it was built) was $2 million. If the spillway were not enlarged, the maximum damage that could occur would be $900,000; if it were enlarged, the maximum damage would be $550,000. Thus, the Corps proposal to spend $2 million to prevent a maximum loss of $350,000 (the maximum loss would occur less often than once each two million years) does not seem defensible. However, the funds were appropriated and the spillway was retrofitted.

People living downstream of Mohawk dam would expect to experience an uncontrolled flood, one larger than the impoundment capacity of the dam, less often than once in 500 years. While flood control dams offer protection in most years, every year dams in the USA are forced to spill the waters of large floods, causing downstream damage. What is a remote chance for each locality is a certainty for the entire USA.

Using a distribution fitted to historical data to predict future storms assumes that future storms will be drawn from the same distribution as past storms. In a world with global climate change and human actions that modify hydrology, the assumption seems doubtful. Climate change will

[1] Two parameter (m_x , σ_x) lognormal, the three parameter (a, m_x , σ_x) lognormal, the two parameter (α , μ) extreme value type 1, and the three parameter (a, b, c) log-Pearson III (Resendiz-Carrillo and Lave, 1987).

increase the precipitation and storm size in some areas and decrease it in others (IPCC, 2001). Knowing that the underlying distribution of large storms will shift makes planning difficult, complicating what authorities should tell people about the likelihood of flooding.

In contrast to river flooding, the number of hurricanes striking the United States is described by a Poisson distribution without anomalous numbers of large events. Even without a "fat tail", the distribution tends to fool people who rely on their memory. In over half the years, Florida had no hurricanes. There have been five-year periods with no hurricanes in the state, and several decades with only two. Only once in 20 years do Floridians experience three hurricanes in a year (only once in sixty years for four hurricanes in a year). During the 150 years of data, no category 5 hurricane got closer to New Orleans than Camille's 40-mile miss in 1969. While some people interpret this history to indicate that a large hurricane will not strike New Orleans during their lifetimes, this view is short-sighted, relying too heavily on a small number of observations.

2. Engineering mistakes

Although significant engineering mistakes are rare in constructing dams, they can cause more damage and loss of life than if the dam had not been constructed. Some spectacular dam failures have occurred, killing hundreds of people, such as Teton dam as it was being filled (National Research Council, 1988; Green, Parker, and Tunstall, 2000).

Similarly, the levees around New Orleans were designed to withstand a category 3 hurricane. In 150 years of data, New Orleans has not experienced more than a category 3 hurricane, although three category 4 and one category 5 have come within 65 miles (NOAA, 2006). The damage that occurred from Katrina (category 3 near the city) was caused by poor engineering and construction, leading to 28 separate levee failures when they should not have failed (Seed et al., 2006). For example, a 1000-foot-wide layer of weak peat soil was the foundation of some levees. This layer was not taken into account in the design, and the levees failed without being overtopped. As another example, pilings designed to extend 17 feet below sea level were driven to a depth of only 10 feet. Figure 1 shows the flooding due to one levee failure.

To a public health official, the possibility of engineering mistakes means that, as occurred in New Orleans, flooding might occur with a storm less serious than it was designed for. Since engineers build in safety factors, sometimes large ones, there is also the possibility that the defense system would handle a larger threat than it was designed to handle. These possibilities force responsible officials to guess rather than make an informed decision.

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3. Perceptions of flooding

When costly floods occur, Congress feels compelled to appropriate funds to help the victims: Helping your neighbor in a time of need is praiseworthy. But, as people move into locations at high risk of flooding, they need to be informed of the consequences of their decisions and to avoid putting a burden on others. The general unavailability of private flood insurance and the growing cost of flood relief led Congress to pass the National Flood Insurance Act of 1968 making subsidized insurance available. However, few people bought the insurance and so Congress passed the Flood Disaster Protection Act of 1973 requiring that houses in a 100 year flood plain have insurance; the Act also required the Army Corps of Engineers to inform people about their flood risks.

Why did people move into flood plains, putting themselves and their property at risk? For those who did, why did they not purchase flood insurance to cover their financial risks?

A first answer is that they are unlikely to know the frequency and magnitude of floods. Public perceptions of the frequency of events that could cause death or injury are inaccurate (Slovic, Fischoff and Lichenstein, 1979). For example, two different groups each listed nuclear power as being the most risky of thirty activities. The two groups ranked motor vehicles as being second and fifth most risky, respectively. Thus people fear nuclear power plants, which have caused no deaths in the USA, more than motor vehicle crashes, which kill about 42,000 people and cause about 4-million injuries each year. A group of risk experts ranked motor vehicles first and nuclear power 20^{th}.

Unless they knew experts' analysis of flood magnitude and frequency, people living in a flood plain could do little more than guess at the likelihood of flooding. Medium and large floods occur less often than once in several decades. Thus, unless people are apprised of the flood risks, and understand and believe the communication, they cannot make informed decisions about where and what to build.

If they believe that floods are unlikely to occur, because of a flood control dam or because no one in the area has experienced a flood, residents are unlikely to value flood insurance. Since this insurance costs up to thousands of dollars per year, people who don't understand its value are likely to resist purchasing it. The large literature on risk perception does not give a satisfactory explanation for the fact that people are willing to purchase fire insurance and liability insurance for their cars when ordered to do so by their mortgage company or the government, but many resist purchasing flood insurance (Fischhoff, 1993; Kunreuther, 1996). Fischhoff (1995) sees communication as the major barrier to getting people to perceive the risks. Johnson et al. (1993) see framing the communication and decisions as a major problem.

Although flood insurance is required to get a mortgage on a house in the flood plain from a federally insured institution, only half of the houses in a flood are insured (Dixon et al., 2006). When a flood occurs, many people rush to buy insurance, presumably because they now realize that the risk is real. However, a large proportion of home owners cancel their insurance as years pass, as if they were gambling against nature that they could predict the next flood and have insurance only in the year it occurred (Lave and Lave,1991). Many people complain that the price of insurance against floods, hurricanes, earthquakes, or other natural disasters is too high; saying that they cannot afford the insurance, they decide to live without it. The National Flood Insurance program is priced, roughly, at the actuarial value. Thus, the price of insurance conveys information about the risks that people don't understand or don't want to know.

People readily buy fire insurance, even though the probability of a fire is less than that of a flood for many people. Banks insist on proof of fire insurance in granting a mortgage. Although they are required to do so by the federal government and they have a financial interest in protecting the mortgaged property against flood loss, banks don't uniformly enforce the flood insurance provision. One bank manager questioned about this claimed that he didn't know about the federal requirement. He then added that his customers complained bitterly about the cost of the flood insurance and he thought that he could lose mortgages if he insisted that they buy the insurance (Lave and Lave,1991). Other than the apparent willingness of people to buy fire insurance and their reluctance to buy flood insurance, we cannot offer an explanation for why banks don't insist that houses in the flood plain be insured.

4. Keeping people out of harm's way

The hurricanes of 2004 and 2005 together with tornados, ice storms, and earthquakes are dramatic warnings that nature is not well-behaved. From 1995 to 2004, natural disasters (including floods, tornados, hurricanes, winter storms, and wind storms) on average killed 638 people per year, injured 4,057, and caused $10.2 billion in property damage in the U.S. (Hazards Research Lab, 2006). Putting a dollar value of $5 million on each premature death and $50,000 on each injury (US Environmental Protection Agency, 1999), the social cost of the premature deaths and injuries was $3.2 billion and $0.2 billion, respectively. Thus, the social cost of property damage is about three times greater than the costs of deaths and injuries. This comparison suggests that great attention is given to protecting lives.

One way to prevent deaths and property losses from natural disasters is to keep people and property out of harm's way by not occupying a vulnerable area. Some jurisdictions prevent people from building in dangerous areas or use other strategies to lessen exposure (Green, Parker, and Tunstall, 2000).

Society can keep people out of areas where natural disasters are frequent and destructive. However, there is no place safe from all 500 year natural disasters (much less all 10,000 year natural disasters). Even areas that don't normally worry about hurricanes are in danger from a 500 year storm. Such a storm could cross Mexico and threaten Los Angeles or travel up the east coast and threaten New York and Boston or even travel up the Mississippi and Ohio Rivers, threatening Pittsburgh. One of the largest USA earthquakes struck New Madrid, Missouri, an area that is not usually thought of as subject to earthquakes.

Knowing the size and frequency of the largest floods (those that might occur once in 10,000 years) is impossible. There is insufficient historical data to estimate even the 500 year flood with confidence. In addition, climate changes over decades, making it impossible to rely on the historical record for predicting large, infrequent floods.

Even if we could predict the largest floods, there is little or nothing we would choose to do. For example, suppose that we knew that a flood largest enough to destroy all the property below the Mohawk dam would occur with an annual likelihood of 1/10,000. Engineers could not build a dam to contain that flood. Government could force people not to build on the land, moving them to find someplace safe from large natural disasters. However, as argued above, there is probably no place on Earth safe from such extremely large events. Attempting to prevent property damage from such large events is foolish. Even for the largest natural disasters that we could protect against with dams, earthquake and hurricane resistant construction, etc., the cost of protection would be far greater than the expected loss that could be presented. Thus, it makes no sense to focus on extreme events.

Rather than focusing on the largest natural disasters where society can do little to prevent damage, we suggest focusing on protecting against small and moderate events. Without care, this strategy could increase expected damage and loss of life. For example, massive development in an area newly protected by a levee could result in massive property damage and even deaths when a large storm occurs.

5. Informing individual's decisions

Rather than mandating a high safety level, society should leave these decisions to individuals, as long as they know the risks and bear the consequences. At a minimum, before allowing development in a vulnerable area, people must be informed of the risks.

Although the USA has spent billions on protective structures, losses from floods and hurricanes have increased (National Research Council, 1988). This is an indication that society has allowed development of vulnerable areas. Whether the development is wise depends on the value of developing the vulnerable and newly protected land. If the dam had not been built, the flood plain would not have been developed and society would have lost the benefit of this development. If the expected benefit exceeds the expected cost, the development makes sense. The 2004 and 2005 hurricanes have not deterred people from rebuilding in Florida or some other parts of the Gulf coast. However, we wonder if people would rebuild in the lower Ninth Ward of New Orleans if they had to purchase flood insurance. In view of the large numbers of uninsured buildings and the billions of dollars in government and private aid, it is clear that the costs have not been recognized correctly in the location decisions.

A rational individual who understands the risks and still chooses to build in the flood plain is revealing that the expected benefit of the development is at least as great as the expected loss. However, if the people enjoying the benefit don't have to pay the cost, because they don't buy flood insurance and have much of their loss paid by government programs and private donors, resources will be misallocated**.**

People can take actions to mitigate the loss of a prospective natural disaster. For example, they can build a house over a garage to get above the flood level; they can install hurricane straps to protect the roof, or build so that a moderate earthquake would not destroy the building. Kleindorfer and Kunreuther (1999) describe the complementary role of mitigation and insurance; if the insurance premium reflects the expected loss, it encourages mitigation.

The completion of a flood control dam often sends people scurrying to develop the newly protection flood plain. Likely, some of the people building or buying structures in the protected plain don't understand the risk. Providing this information to people is not easy (Fischhoff, 1995). One way is to require natural disaster insurance that is actuarially fair. Knowing the cost of an annual insurance premium helps people understand the risks in a way that telling them of the frequency of a natural disaster does not. Similarly, allowing buildings in earthquake-prone areas can make sense if the owner and tenants are aware of the risks and are willing to pay for insurance.

By encouraging development in vulnerable areas, especially those now protected by a dam or other structure, society is increasing the damage and possible loss of life if a larger natural disaster strikes. Simply put, a large natural disaster will destroy large amounts of property.

6. Information as a remedy

Society is caught in a dilemma. Individuals should be free to make their own risk decisions, but only if they bear the consequences. There is no getting around the fact that Americans want to help others in need. This is a laudable trait. But if it encourages people to locate in places with frequent natural disasters, it increases the physical and financial risk and burdens society with periodic bailouts (Camerer and Kunreuther, 1989).

As the *Washington Post* wrote in a September 21, 2005 editorial, "But the truth is that, after a disaster like Katrina, the federal government will bail everybody out whether they are insured or not; it's humanly and politically unthinkable to do otherwise. Because the likelihood of a federal rescue is so strong, there never was much incentive to buy insurance." Elliott (2005) estimates that a homeowner loses $1 of federal disaster relief aid for every $3 of flood insurance loss payments, in addition to losing charitable help.

We agree that it is unthinkable that the government would not provide rescue and humanitarian relief services after a Katrina. However, whether FEMA provides grants and low interest loans for recovery is not so automatic. An area is declared a federal disaster area only when there is widespread loss. If almost all people are insured, the few who are not might not get a sympathetic public hearing for assistance in rebuilding.

We suggest that individuals would make more informed decisions if the expected losses were charged annually in the form of an insurance premium covering the loss. People should know the premium when deciding where to locate. Kleindorfer and Kunreuther (1999) further suggest that insurance could help to shape mitigation decisions by adjusting the payment to reflect measures to lower the frequency and level of loss. For mitigation measures that are inexpensive and effective, transactions costs might make it more efficient to simply require the measure, e.g., hurricane straps.

Consider an ocean front house in Florida listed at $1 million. On a beautiful day, a prospective buyer is unlikely to be concerned about hurricanes, especially if she talks to people living nearby who report that they have never experienced a hurricane. Further suppose that an actuarially fair insurance premium would be $30,000 per year for the house. At a 10% interest rate, the present discounted value of the insurance is $300,000, suggesting that property worth $1 million without a hurricane risk ought to sell for $700,000 recognizing the risk and insuring against it. If the insurance were required, the prospective buyer would get the best available information in a form that is hard to ignore or misinterpret. Prohibiting people from building on the property because society doesn't want to pay for storm losses would be less efficient than requiring insurance.

In the absence of mandatory insurance, the most efficient policy might be strict zoning and building standards. Information is a substitute for regulation in the sense that individuals could be informed about the risks of buying a house without hurricane straps or a house located within the 100 year flood plain. Unfortunately, giving this information to prospective buyers in a way that they can understand and appreciate is not simple (Fischhoff, 1995). An externality that is important in some cases is damage to neighboring homes or public structures due to windblown debris from structures without hurricane straps.

7. The paternal libertarian

Society requires individuals to buy liability insurance in order to drive a car. Society requires that workers pay into an unemployment insurance fund and employers to pay into a workers' compensation fund. Libertarians protest, arguing that individuals should decide for themselves when to buy natural disaster insurance. However, as long as society is going to bail out individuals who didn't have insurance, the libertarian argument rings hollow. If there is no credible way for individuals to renounce a later bailout, they cannot be free to opt out of insurance.

Thaler and Sunstein (2003) have developed the notion of "libertarian paternalism" which leaves individuals with a choice, but makes it more difficult to opt out. Here, for example, individuals might be allowed to opt out of insurance if they took an hours-long course on the dangers and likelihood of natural disasters and then made a video in which they stated that they understood the reasons for the insurance, but preferred to self-insure and swore that they would not accept public grants or loans if they suffered a loss. We think that most individuals would find opting out troublesome and we hope that the public would harden their hearts to individuals who had recorded such a statement, aside for immediate humanitarian help.

8. Protecting people or property?

When human lives are at risk, decision making is rarely rational (Viscusi, 1993; Tengs et al., 1995). When the government insists that a dam be retrofitted to pass a PMF, they are putting an extremely high value on not losing a life due to dam failure. Lave, Resendiz-Carrilla, and McMichael (1990) conclude that lives could be protected at much lower cost with a warning and evacuation system. EPA conducts analyses with a dollar value of morbidity and mortality; however, many government agencies are reluctant to follow their lead.

Large storms in 1953 caused massive damage and loss of life in the Netherlands. The result has been hard-nosed calculations about how much protection to build against large storms (Van Dantzig, 1956). They understand that they cannot protect against the largest storm and have done explicit benefit-cost analyses of how much to spend on flood protection (Vrijling, 2001). The conclusion of the analyses was adopted.

9. The benefits of warning

If, as we recommend, society focuses on protection against small and medium size events, a large event will cause major property loss and number of deaths. Agencies are comfortable conducting a benefit-cost analysis concerning property losses but not deaths. Thus, one key to improving government decision making is to prevent massive loss of life. Rather than trying to protect people where they live, work, or recreate, society should improve programs to evacuate them out of harm's way.

Except for earthquakes, people have days or at least hours of warning before natural disasters (Paté-Cornell, 1985). The National Hurricane Center has developed an exemplary way of warning people, starting with news of a tropical depression developing in the Atlantic, and then giving frequent updates on the intensity of a storm and probabilities for where it is likely to strike. That system could be extended to all natural disasters (except earthquakes). The National Hurricane Center warnings have reduced the number of deaths from hurricanes from 14,000 during the decade from 1900-1909 to less than 1,000 during the decade from 1980-99, with a slight annual increase from 2000-2004, despite greatly increased coastal populations. Warning systems also exist for floods, high winds, and tornados.

Warning and evacuation are not always simple matters (Paté-Cornell, 1985). The failure to evacuate New Orleans in 2005 when Katrina was forecast indicates the reluctance of public officials to order an evacuation with its large costs, possible breakdown of civil order, and the possibility of deaths and injuries resulting from the evacuation itself (and the possibility of ordering evacuation when it turns out not to be needed). A mandatory evacuation was finally ordered 20 hours before the hurricane struck, too late for effective action.

A decision to evacuate under uncertainty must balance the costs of a false positive (evacuation when it isn't needed) against the costs of a false negative (not evacuating when warranted).

Given its crucial role, more needs to be done to understand the conditions under which evacuation should be ordered, or even advised, and more planning is needed on how to carry it out. In ordering an evacuation, the government takes responsibility for harm that might come to the evacuees, at least in principle. This would include highway crashes in the evacuation and problems with housing and food where people are relocated. The problems become especially acute for residents of nursing homes and hospitals who are not capable of making evacuation decisions. Moving these people puts them at risk – as does not moving them. If a government is financially responsible for ordering an evaluation, public officials face an asymmetric loss function: They assume liability if they order evacuation but not if they merely warn people to leave. Even without the threat of financial liability, public health officials are reluctant to order evacuations.

Officials would make better decisions if the false positive costs are reduced. For example, if evacuation planning lowered traffic deaths and got people to adequate shelter, evacuations would be ordered more frequently. Another step would be to locate nursing homes and hospitals in places where evacuation would not be necessary. This location would relieve the pressure on public health officials agonizing about ordering an evacuation, and would save lives among the injured and infirm who would not have to be moved. Perhaps most valuable would be finding ways to speed the evacuation so that officials could wait until "the last minute" to decide. Given the uncertainty of where a hurricane will land, there is much to be gained by being able to delay the evacuation decision.

The difficulties with evacuation grow more than proportionally to the number of people evacuated and the distance they are moved. Among the 3.7 million Texans who left in advance of hurricane Rita, there were 60 evacuation-related deaths. Assuming that people stayed away for three days at a cost of $100 per person-day and valuing the fatalities at $5 million, the evacuation cost $1.4 billion . In this case, the evacuation wasn't needed. The high cost of evacuation requires a hard look at the costs and benefits. If less than 220 people would have died absent an evacuation and people would not have faced the displacement cost, social costs would have been lower by not evacuating. A public health official must balance the high cost of evacuating a large city against the expected loss of life from not evacuating. As Rita showed, uncertainty about the number of deaths from not evacuating together with the certainty of deaths and expenditures from evacuating may paralyze public officials.

Evacuation is an important area for research and community discussion. Research is needed to estimate the costs of evacuation and the likely number of deaths if there were no evacuation. The community discussion is needed to lay out the alternatives and have people decide on the best alternative. Benefit-cost analysis that values premature death at $5 million is not likely to be a good description of how people want government officials to tradeoff evacuation costs against lives lost.

10. Planning for future natural disasters

The hurricane seasons of the past two years are unprecedented. They may represent the 200 year season (we have only 150 years of data) or a new regime due to global climate change or other non-stationary processes. There is no way to know which is true without many more years of data. For example, the 2006 hurricane season could be as bad as the previous two years. If so, that could indicate that we are experiencing the 200-year storm pattern or that the distribution has shifted, due, for example, to climate change (Emanuel 2005a, 2005b).

More people and property are locating in areas at risk from hurricanes and other natural disasters. Florida had 2.8 million inhabitants in 1950 and 16 million in 2000. The market value of property in Miami doubled between 1992 (when hurricane Andrew passed nearby) and 2004. As the population of the USA increases and grows richer, people want to live in coastal areas and warmer climates. There is no question of the need to rethink policies regarding natural disasters.

11. Summary

We summarize our major themes:

1. Public policy regarding extreme natural disasters is needed. While rare in any one place, these disasters occur frequently in the USA and the data suggest that individuals and government are poorly prepared when they occur.

2. Explicit minimization of the costs of protection plus present discounted losses can lower social losses and lead to more efficient resource allocation.

3. Society should focus on public policies that protect against small and medium size natural disasters, but make sure that people deciding to live in an area at risk understand the consequences of their decisions, bear the expected loss through mandatory insurance, and can be evacuated if a large disaster strikes. Mandatory insurance not only forces people to bear the costs of their decisions, but also has the bonus of providing people with information on the risks they face.

4. Further research is needed on why so many people refuse to buy insurance against natural disasters, despite their willingness to buy insurance against fires and vehicle crashes. Research is also needed to examine the tradeoffs between decisions to evacuate that turn out not to be necessary and decisions not to evacuate when evacuation is needed.

5. A paternalistic libertarian approach might allow a few people to extricate themselves from mandatory insurance, while ensuring that they have the proper information, understand the consequences, and will not claim society's resources if catastrophe occurs.

6. Rare, extremely large natural disasters have to be considered in terms of protecting lives. Protecting people where they live and work in not feasible. Evacuation is the only realistic way to protect lives. This means developing policies to evacuate people quickly and safely and to provide them with safe shelter. More resources are needed here, together with community discussions to get people to understand risks and guide public decisions.

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References

Camerer, Colin F. and Howard Kunreuther. (1989). “Disaster Processes for Low Probability Events: Policy Implications,” Journal of Policy Analysis and Management 8, 565-592.

Dixon, Lloyd, Noreen Clancy, Seth A. Seabury, and Adrian Overton. (2006), “The National Flood Insurance Program’s Market Penetration Rate,” The RAND Corporation Technical Report TR-300. Available at: http://www.rand.org/pubs/technical_reports/2006/RAND_TR300.pdf.

Elliott, Douglas (2005). Testimony before the Senate Committee on Banking, Housing, and Urban Affairs, October 18, 2005. Available at: http://banking.senate.gov/_files/elliott.pdf

Fischhoff, Baruch (1993). “Transaction analysis: A framework and an application to insurance Decisions,” Journal of Risk and Uncertainty 7, 53-69

Fischhoff, Baruch (1995). “Risk Perception and Communication Unplugged,” Risk Analysis 15, 137-45.

Emanuel, Kerry (2005a). “Increasing destructiveness of tropical cyclones over the past 30 years,” Nature 436(7051), 686-688.

Emanuel, Kerry (2005b). “Meteorology: Emanuel replies,” Nature 438(7071), E13.

Green, C.H., D.J. Parker, and S.M. Tunstall. (2000). “Assessment of Flood Control and Management Options,” World Commission on Dams, P.O. Box 16002, Vlaeberg, Cape Town 8018, South Africa. Available at: http://www.wca-infonet.org/servlet/BinaryDownloaderServlet?filename=1067095619090_report.pdf.

Hazards Research Lab. (2006). “The Spatial Hazard Events and Losses Database for the United States, Version 4.1” [Online Database]. Columbia, SC: University of South Carolina. Available at http://www.sheldus.org.

Intergovernmental Panel on Climate Change (IPCC). (2001). “Third Assessment Report.” Available at http://www.ipcc.ch/

Johnson, Eric J., John Hershey, Jacqueline Meszaros, and Howard Kunreuther. (1993). “Framing, Probability Distortions, and Insurance Decisions,” Journal of Risk and Uncertainty 7, 35-51.

Kleindorfer, Paul R. and Howard Kunreuther. (1999). “The Complementary Roles of Mitigation and Insurance in Managing Catastrophic Risks, Risk Analysis 19, 727-38.

Kunreuther, Howard. (1996). “Mitigating Disaster Losses Through Insurance,” Journal of Risk and Uncertainty 12, 171-87.

Lave, Lester, Daniel Resendiz-Carrilla, and Francis McMichael. (1990). "Safety Goals for High-Hazard Dams: Are Dams Too Safe?," Water Resources Research 26, 1683-1691.

Lave, Tamara R. and Lester B. Lave. (1991). "Public Perception of the Risks of Floods: Implications for Communication," Risk Analysis 11(2), 255-267.

National Hurricane Center, "The Deadliest Atlantic Tropical Cyclones, 1492-1996," available at http://www.nhc.noaa.gov/pastdeadly4.html

National Oceanic and Atmospheric Administration (NOAA), "Historical Hurricane Tracks" (2006). Available at http://hurricane.csc.noaa.gov/hurricanes/.

National Research Council, Committee on the Safety of Existing Dams. (1985). *Safety of Existing Dams: Evaluation and Improvement*. Washington: National Academy Press.

National Research Council, Committee for Estimating Probabilities of Extreme Floods. (1988). *Estimating Probabilities of Extreme Floods: Methods and Recommended Research*. Washington: National Academy Press.

Paté-Cornell, M. Elisabeth (1985). "Warning Systems and Risk Reduction," in Chris Whipple and Vincent T. Covello (eds), *Risk Analysis in the Private Sector*, 469-482, New York: Plenum.

Resendiz-Carrillo, Daniel and Lester B. Lave. (1987). "Optimizing Spillway Capacity with an Estimated Distribution of Floods," Water Resources Research 23(11), 2043-2049.

Resendiz-Carrillo, Daniel and Lester B. Lave. (1990). "Evaluating Dam Safety Retrofits with Uncertain Benefits: The Case of Mohawk Dam (Walhonding River, Ohio," Water Resources Research 26(5), 1093-1098.

Seed, Raymond B. et al. (2006). *Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005,* report of the Independent Levee Investigation Team. Available at http://www.ce.berkeley.edu/~new_orleans/.

Slovic, Paul, Baruch Fischhoff, and Sarah Lichtenstein (1979). "Rating the risks." Environment, 21(4), 14-20, 36-39.

Tengs, Tammy O., Miriam Adams, Joseph S. Pliskin, Dana G. Safran, Joanna E. Siegel, Milton C. Weinstein and John D. Graham. (1995). "Five Hundred Lifesaving Interventions and Their Cost-Effectiveness," Risk Analysis 15(3), 369-390.

Thaler, Richard H. and Cass R. Sunstein. (2003). "Libertarian Paternalism," The American Economic Review 93(2), 175-179.

United States Environmental Protection Agency. (1999). "The Benefits and Costs of the Clean Air Act, 1990 to 2010," Appendix H. Available at: http://www.epa.gov/oar/sect812/copy.html

Van Dantzig, D. (1956). "Economic Decision Problems for Flood Protection," Econometrica 23, 276-289.

Viscusi, W. Kip. (1993). "The Value of Risks to Life and Health," Journal of Economic Literature 31(4), 1912-1946.

Vrijling, J.K. (2001). **"**Probabilistic design of water defense systems in The Netherlands," Reliability Engineering and System Safety, 74, 337-344.

Appendix

To derive the optimal size dam and spillway for a site, we use the same notation introduced in the text, and proceed as follows. Society seeks to minimize the sum of the present discounted loss from flooding (PDL) and the cost of building a dam and spillway. For many locations, building a dam and spillway will lower the sum of the two costs. If not, no dam should be built.

The purpose of a spillway is to prevent catastrophic dam failure if the flood is larger than the dam can impound. Catastrophic dam failure occurs when the flood is larger than the spillway can handle; it can result in a wall of water going downstream, causing vast losses, as well as requiring extensive repairs on the dam.

Assume that a dam is built that can impound a flood of size x and a spillway is built that can handle a flood of size y without harming the dam. For a particular location and distribution of floods f(w), society seeks to choose x and y to minimize the sum of the construction costs and present discounted losses:

Social Loss = D(x) + S(y) + PDL(x,y) (A1)

$$Min\ Z = D(x) + S(y) + \int_x^y \frac{L(x)\,dx}{(1+i)^{T(x)}} + \int_y^\infty \frac{L(y)\,dy}{(1+i)^{T(y)}} \quad \text{(A2)}$$

$$\frac{\partial Z}{\partial x} = \frac{dD}{dx} - \frac{L(x)}{(1+i)^{T(x)}} = 0 \quad \text{(A3)}$$

$$or \quad \frac{dD}{dx} = \frac{L(x)}{(1+i)^{T(x)}} \quad \text{(A4)}$$

This first order condition tells us to increase the size (impoundment capacity) of the dam until the additional cost of another unit of expansion is equal to the present discounted loss of flooding prevented by the dam expansion.

$$\frac{\partial Z}{\partial y} = \frac{dS}{dy} + \frac{L(y)^*}{(1+i)^{T(y)}} - \frac{L(y)^{**}}{(1+i)^{T(y)}} = 0 \quad \text{(A5)}$$

$$or \quad \frac{dS}{dy} = \frac{-L(y)^*}{(1+i)^{T(y)}} + \frac{L(y)^{**}}{(1+i)^{T(y)}} = 0 \quad \text{(A6)}$$

Where L(y)* is the loss from flooding from a storm of size y that is spilled over the spillway and L(y)** is the loss from flooding from a storm of size y that is spilled and which causes catastrophic failure of the dam. This first order condition tells us to increase the size of the spillway (the ability to protect the dam from catastrophic failure) until the additional cost of another unit of expansion is equal to the present discounted loss due to the additional loss from catastrophic dam failure.

Tables

Table 1. Observed and predicted floods for two rivers.

River	Mean maximum flood (meters^3 per second, CMS)	Largest observed flood (CMS)	Estimated 500 year flood (CMS)	Probable maximum flood, PMF (CMS)	Return period for PMF (years)
Rio Grande 1884-1984	146	470	547 - 928	850	350 - 11 x 10^6
Walhonding 1922-1987	570	2,000	1,850 - 2,640	10,800	2.2 x 10^6 - 4.6 x 10^{15}

Figure Legends

Figure 1. Breach in the New Orleans 17th street levee, August 31, 2006. The glint of the sun brightens the flood in places. U.S. National Oceanic and Atmospheric Administration photograph.

Figure 1