Estimating Flood Impacts: A Status Report

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Abstract
Policy makers face a range of options to improve flood protection, including physical barriers, improved water network management, relocation, and environmental improvements such as marshland and barrier restoration. Determining the best protection option(s) requires estimates of costs and effectiveness and an estimate of the flood damages that would be avoided.

Efforts to obtain this information have increased over the past decade as concerns regarding potential sea level rise related to climate change have grown. Recent large scale flooding events such as Hurricane Sandy have also prompted greater attention. In the United States, the Army Corps of Engineers developed the HAZUS model to address both property and contents damage from flooding. The model, managed and distributed by the Federal Emergency Management Administration, is capable of translating flood characteristics such as flood extent, depth, and duration. California's Department of Water Resources, for example, used the model to estimate potential flood damage in all 58 counties (California Flood Future 2013). More recently, the California Coastal Commission sponsored a study to compare investment in marshland restoration in the San Francisco Bay area to the value of expected flood damage avoided using HAZUS (SF Bay Area Economic Institute, URS, and the Brattle Group, 2015).

HAZUS does not tell the whole story on damages, however. While it covers property losses it does not capture other costs such as infrastructure damage (bridges, highways, electricity network facilities (substations, power lines, etc.)) and agricultural losses. Fortunately, there are well developed methods of quantifying these losses as well. Flood maps can also provide the basis for determining infrastructure repair costs, and whether and to what extent transportation networks (air, rail, highway) will be out of service because of flood waters. There is a well-developed literature on costs associated with travel delay and utility service interruptions.

In sum, methods are available to make reasoned estimates of flood damages necessary to make informed flood management decisions.

Keywords: Flooding, flood modelling, damage modelling, wetlands, cost–benefit.

1. Introduction
Although efforts have been underway since the 1960s to estimate flood damages for purposes of prevention planning, greater attention has been paid to this area in the last decade or so in response to a series of large scale flood events around the world and increasing concern for rising ocean levels attributed to climate change. This effort has been facilitated by improved data collection, GIS, and satellite imagery. As a consequence, estimating flood damage is considerably further advanced than similar efforts for other natural disasters. This is not to say that definitive methods are available, but it is the case that methods are available that can provide policy makers and private property owners with highly useful information regarding the value of flood prevention. This paper reviews the data and methods typically employed in flood impact models, discusses some of the issues that remain, and identifies some areas where further efforts are required to make flood impact models more reliable and accessible.

2. Background
Floods are the most frequent form of natural disaster and among the most costly to both human life and property. Worldwide, the economic damage from flooding has been substantial. Flooding in Thailand in 2011 caused an estimated $40 billion, flooding in China in 1998 cost an estimated $30 billion. Other floods in the United States, Korea, Pakistan, and Germany, between 1998 and 2011, cost between $9.5 and $18 billion.[1] See Figure 1. According to National Weather Service data, U.S. floods have cost between $0.5 billion and $56 billion every year since 1903, averaging $5.4 billion.[2] Deaths attributable to these floods have averaged around 100 per year. See Figure 2 and Figure 3. These floods are at coastal locations and along riverbeds.

[1] Statistics from CRED (Centre for Research on the Epidemiology of Disasters).

[2] U.S. National Weather Service, Department of Commerce.

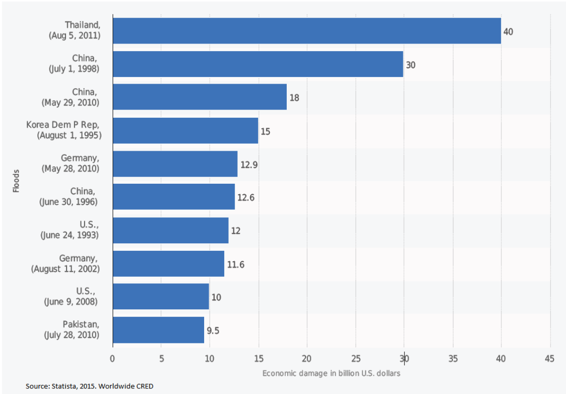

Figure 1 Economic Damage caused by significant floods worldwide from 1993 to 2014* (in billions of U.S. dollars)

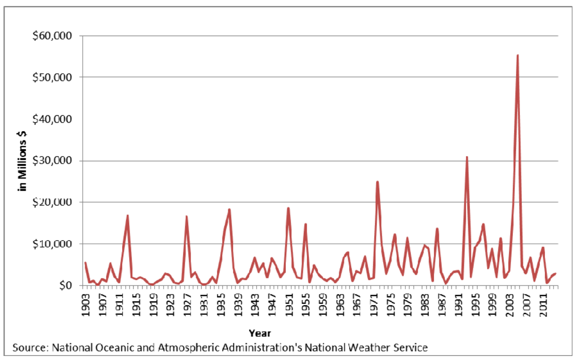

Figure 2 Flood Damages in the United States (Water Year) in Millions 1903-2014

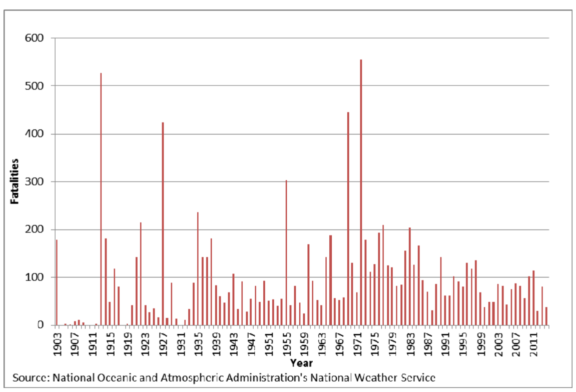

Figure 3 Flood Fatalities in the United States 1903-2014

Concerns about growing coastal flood risk have led to multiple studies of potential damages at port cities throughout the world. One study estimated that as of 2005, about 40 million people across 136 port cities were exposed to a 1 in 100 year coastal flood event. The total value of assets associated with this exposure was calculated at US $3,000 billion.[3] Sixty five percent of the population exposed to this risk are located in Asia. North America accounts for about 21 percent while South America accounts for under 2 percent and Australasia accounts for less than 1 percent. The distribution of assets at risk is different, reflecting greater development in North America, which represents about 50 percent of total assets. These distributions are projected to change over the next fifty years because projected population growth, economic development, and sea level rise. In 2070, Asia is expected to account for the largest population and asset exposure. Table 1 lists the port cities with the greatest exposure in 2005 and 2075.

Table 1 Top 20 cities ranked in terms of assets exposed to coastal flooding in the 2070s (including both climate change and socioeconomic change) and showing present-day exposure

Rank	Country	Urban agglomeration	Exposed assets—current ($Billion)	Exposed assets—future ($Billion)
1	USA	Miami	416.29	3,513.04
2	China	Guangzhou	84.17	3,357.72
3	USA	New York-Newark	320.20	2,147.35
4	India	Kolkata (Calcutta)	31.99	1,961.44
5	China	Shanghai	72.86	1,771.17
6	India	Mumbai	46.20	1,598.05
7	China	Tianjin	29.62	1,231.48
8	Japan	Tokyo	174.29	1,207.07
9	China	Hong Kong	35.94	1,163.89
10	Thailand	Bangkok	38.72	1,117.54
11	China	Ningbo	9.26	1,073.93
12	USA	New Orleans	233.69	1,013.45
13	Japan	Osaka-Kobe	215.62	968.96
14	Netherlands	Amsterdam	128.33	843.70
15	Netherlands	Rotterdam	114.89	825.68
16	Vietnam	Ho Chi Minh City	26.86	652.82
17	Japan	Nagoya	109.22	623.42
18	China	Qingdao	2.72	601.59
19	USA	Virginia Beach	84.64	581.69
20	Egypt	Alexandria	28.46	563.28

Source: Table 3. Hanson, S. et.al, "A global ranking of port cities with high exposure to climate extremes," Climatic Change (2011) 104:89-111.

Although not in the top 20 based on exposed assets, many other cities and towns throughout the world face serious and frequent flood risks. In New Zealand, for example, substantial flooding is almost an annual event. According to data from the Insurance Council of New Zealand, flooding has resulted in large damage claims every year since 2000 with the exception of 2012.[4] Claims totalled NZ$142 million during the period (in 2015 dollars). Insurance claims account for only a fraction of total damage.[5] Australia also faces serious flood risk. Annual flood related damages were estimated at A$377 million for the period

3 Hanson, S. et.al, "A global ranking of port cities with high exposure to climate extremes," Climatic Change (2011) 104:89-111.

4 Insurance Council of New Zealand, "Historical Events," http://www.icnz.org.nz

5 According to BITRE, "Economic Costs of Natural Disasters in Australia," Report 103, 2001, p. 13, insurance claims may represent only 10% of total damages.

1967–2005.[6] Extensive flooding in 2011 resulted in damages in excess of A$2.38 billion.[7]

3. Model Review

The statistics and projections presented above make clear the importance of flood mitigation efforts in many areas of the world. This is not news and in fact flood prediction methods and flood impact modeling have been a focus of considerable research for more than 60 years.[8] The sophistication of these models has grown considerably over this period. The introduction of high velocity computing, GIS, and the availability of satellite imagery has accelerated model development over the last decade or two. The recognition of the need for better data has also resulted in more detailed and consistent data sets in many countries.

Today, there are a variety of well-developed models and databases available to government agencies, researchers, corporations, and land owners. There are at least 12 such models although they cover only about 6 countries. See Table 2. The transferability of these models to other countries is not guaranteed, but there are successful examples.[9] Several large insurance companies including Swiss Re, Munich Re, and AON, have developed internal models as well.

These flood impact models have several basic components as shown in Figure 4:

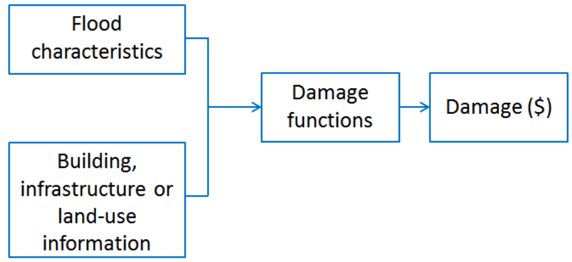

Figure 4 Flood Impact Model

	Models (references)	Country	Development	Functions
1	Anuflood (NR&M, 2002)	Australia	Empirical	Absolute
2	RAM (NRE, 2000)	Australia	Empirical-synthetic	Absolute
3	FLEMOcs (Kreibich et al., 2010)	Germany	Empirical	Relative
4	Model of MURL (MURL, 2000)	Germany	Empirical	Relative
5	Model of Hydrotec (Emschergenossenschaft and Hydrotec, 2004)	Germany	Empirical	Relative
6	Model of ICPR (ICPR, 2001)	Germany	Empirical-synthetic	Relative
7	Model of LfUG, Saxony (LfUG, 2005)	Germany	Empirical-synthetic	Relative
8	Model of Multicoloured manual (MCM) (Penning-Rowsell et al., 2005)	UK	Empirical	Absolute
9	HAZUS-MH (FEMA, 2003; Scawthorn et al., 2006)	USA	Empirical-synthetic	Relative
10	Damage Scanner (Klijn et al., 2007)	Netherlands	Synthetic	Relative
11	Flemish Model (Vanneuville et al., 2006)	Belgium	Synthetic	Relative
12	Rhine Atlas (ICPR, 1998)	Germany	Empirical-synthetic	Relative
13	JRC Model (Huizinga, 2007)	European	Empirical-synthetic	Relative

Table 2 Comparison of different flood damage models

Flood characteristics typically include flood extent, depth, and duration and sometimes include flow rate (water velocity), rise rate and water quality with respect to contamination and debris. This information is obtained from hydrological forecasts and flood history. Models based on simulation exercises are often referred to as synthetic while those based on evidence from previous floods are referred to as empirical. Many models are based on some combination of sources.

The impact of these factors on buildings (residential, commercial, and industrial), infrastructure (bridges, highways, airports), and utilities (electric, natural gas, water and waste water) are estimated based on some form of damage function. These functions link flood characteristics to damages of structures (and in some cases land). A simple function may describe the relationship between flood depth and particular building type, a two story residential building without a basement, for example. For example, a 2ft flood depth may result in a 10 percent reduction in value based on repair costs while a 4ft flood depth results in a 30 percent reduction. Figure 5 presents an example of such a damage function. Contents damage rise with flood depth until a depth of 1 meter is reached at which point,

6 BITRE, "About Australia's Regions – June 2008, Department of Infrastructure, Transport, Regional Development and Local Government, 2008.

7 Carbone, D. and Hanson, J, "Floods: 10 of the Deadliest in Australian History," Australian Geographic, March, 08, 2012.

8 The earliest flood damage curve estimates have been attributed to Gilbert F. White, "Human Adjustment to Floods," University of Chicago, Department of Geography, 1945.

9 See for example, Walton, M. et al., "Economic Impacts on New Zealand of Climate Change Related Extreme Events. Focus on Fresh Water Floods. Report to the New Zealand Climate Change Office, 2004 and B. Jongman et al., "Comparative flood damage model assessment: towards a European Approach," Natural Hazards and Earth System Sciences, 12, 3733-3752, 2012.

contents are ruined. Structural damage for a brick veneer building rise rapidly until about 0.5 meters, but continue to rise as flood depth increases. Figure 6 presents a damage function accounting for water velocity. The areas to the left of the curves reflect no structural movement, while the areas to the right reflect structural movement. Curve shape does not vary by structure type, but as shown in the figure, building materials matter. Brick withstands flood waters better than timber. The importance of velocity and other characteristics is the subject of some debate in the literature and models vary with respect to which characteristics they include. Damage functions are also distinguished by whether they present absolute or relative damage estimate. The two examples presented above are relative damage functions. They present percent changes in damages as a function of depth or depth and flow. Other functions present fixed damage amounts for particular objects (residential structures for example) exposed to specific flood depths and other flood characteristics. The former is more common as shown in Table 2.

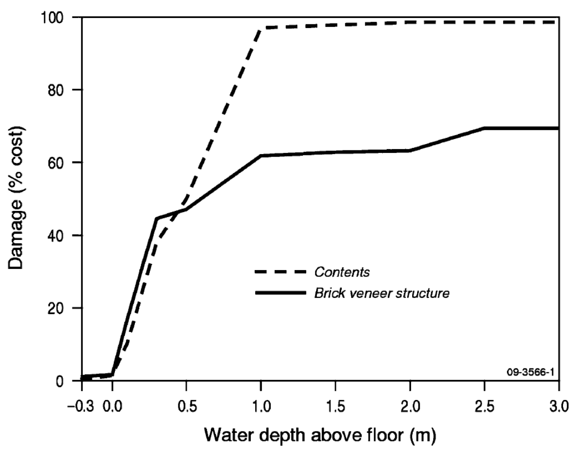

Figure 5 Flood Cost Curve

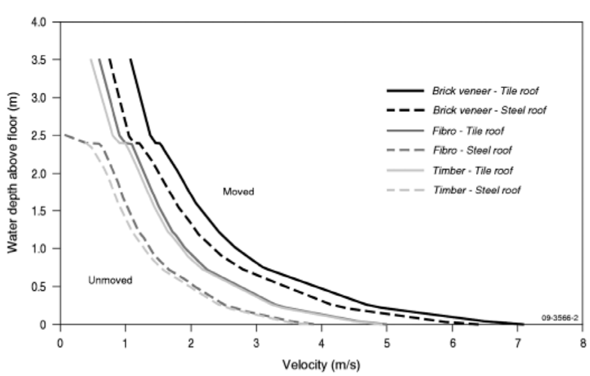

Figure 6 Flood Structural Damage Reflecting Velocity

Another important distinction among damage functions is whether they account for depreciated costs or replacement costs. The majority of damage functions refer to depreciated costs. This is the case in order to provide a measure of the actual loss attributed to the flood event. Replacement costs may be necessary to estimate economic impacts, but the actual loss is the appropriate measure for cost- benefit studies where government expenditures for flood prevention and compared to the loss avoided.

Using model generated flood damage estimates also requires the determination of the likelihood of flood events. Referring back to Figure 5, there would be another box where this probability is applied to the damage estimate to calculate an expected value, which can be compared to flood mitigation costs and expected effectiveness. Research regarding flood probabilities is another area where efforts have been underway for many years. Climate change concerns have accelerated this effort and the collection of better data is leading to better forecasting capabilities.[10]

Like all models, flood impact models are only as good as the data relied on. The development of the necessary data has been underway in many parts of the world for a long period. Consequently, high quality data exists in many locations including the United States, the UK, and Germany. The European Union has sponsored a major project to improve data.[11] Efforts are also underway to varying degrees in other parts of the world including Australia, New Zealand, and Thailand. Geoscience Australia, for example, has established a flood studies database and the National Exposure Information System (NEXIS).[12] These sources are designed to help local governments prepare flood policy studies and project assessments.

Finally, the reliability of the various models remains a subject of concern and research. There have only been a few studies comparing model predictions to actual flood events. There are no standard error terms that can be applied to the model results. Sensitivity analysis has provided the only way to account for variation in outcome.[13]

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10 See for example, Dartmouth Flood Observatory http://floodobservatory.colorado.edu

11 The European Union created Floodsite in 2004 to develop better data across Europe.

12 Geoscience Australia, hazards@ga.gov.au and www.ga.gov.au/scientific-topics/hazards/risk-impact/nexis#heading-2.

13 See for example, Tate, Eric, et al. "Uncertainty and Sensitivity Analysis of the HAZUS-MH Flood Model," Natural Hazards Review (2014) and Bubeck, P. et al., "How reliable are projections of future flood damage?" Natural Hazards Earth Systems Science, 2011.

4. A Recent Application of a Flood Impact Model

A recent application of the U.S. Federal Emergency Management Agency (FEMA) damage model referred to as HAZUS provides a useful example of how flood models can be applied to policy analysis and investment decision making.[14] The Bay Area Council Economic Institute, concerned about flood risk in the San Francisco Bay area, recently conducted an impact study based on what was defined as a severe storm.[15] The storm was described a multiple day event with heavy rains of magnitudes consistent with a storm experienced once in 150 years. Hydrologists were retained to determine the flood characteristics with respect to extent, depth and duration. This information was provided using GIS. Figure 7 presents the extent of expected flooding (blue areas represent the highest flood levels). This information, at U.S. Census tract levels, could be used to run the HAZUS model. FEMA makes the model available for download. HAZUS accounts for building types (residential, commercial, and industrial) and certain building characteristics including height and foundation type. The model generates cost estimates (on a depreciated basis) for structural repair and content loss. These costs are based on cost curves generated by a combination of Federal Flood Insurance Administration and the Army Corps of Engineers (ACOE). A recent study by the ACOE of a creek in the region provided relatively recent and local cost data.[16] Damages related to structural damages totaled $5.9 billion. Damages related to content loss totaled $4.1 billion.

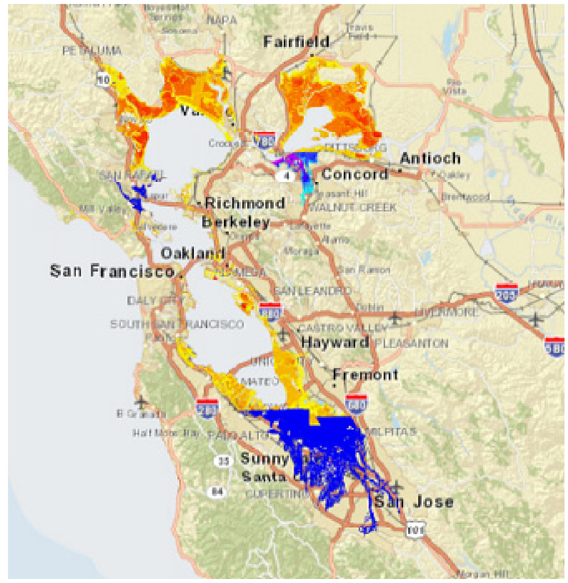

Figure 7 Flood Map for Severe Storm in SF Bay Area

Structural and content damages attributable to the severe storm were estimated fairly readily using HAZUS. The model is well documented and a user with training and experience in modeling, GIS, and economic analysis can become reasonably proficient in a matter of weeks.

Importantly, the model was not used to estimate infrastructure and utility flood damages. Based on the hydrology modeling, the highway system, airports, and the electric utility would all experience some flooding as a consequence of the severe storm. Alternative methods were employed for these sectors. In the case of the highway system, a methodology developed by the ACOE was adopted which relies on a standard assumptions regarding: 1) the amount of delay time resulting from closed roads (30 to 60 minutes) 2) the day of week the flood occurs (each day is equally likely); and the value of travel time per driver (54 percent of family median income).[17] The flood duration was taken from the hydrology analysis, and traffic counts on affected roads were obtained from U.S. Department of Transportation data. A Monte Carlo simulation was used to produce a most likely delay-related impact. Delay costs were estimated to be about $78 million. No serious physical damages to highways or bridges were anticipated based on the flood characteristics.

Economic damages from airport flooding were also based on delay costs. Projected flood characteristics, especially duration for two major airports (San Francisco and Oakland), were used to measure delay. The duration-based delay periods were introduced to a travel delay model

[14] More details regarding HAZUS may be found at: http://www.fema.gov/hazus. A useful description of model methodology can be found in Scawthorn, C. et al., 2006, “HAZUS-MH Flood Loss Estimation Methodology II, Damage and Loss Assessment.”

[15] Bay Area Economic Institute, “Surviving The Storm,” March, 2015, http://bayareaeconomy.org/media/files/pdf/SurvivingTheStorm.pdf

[16] Army Corps of Engineers, 2011, San Francisquito Creek—Preliminary Flood Damage Analysis

[17] Army Corp of Engineers, 2011.

created for the Federal Aviation Administration.[18] This model accounts for delays throughout the airline system caused by delays at individual airports. Delays in passenger hours are translated into delay costs. These costs totaled $86 million. The value is modest because no serious physical damage was anticipated, based on flood characteristics, which resulted in delays measured in hours rather than days.

Electric utility disruption costs were based on methods typically employed by these utilities to quantify loss of load costs. The local utility was asked to review the project flood extent, depth and duration to determine whether any generation, transmission, or distribution facilities would be interrupted. The utility, in a preliminary analysis, determined that approximately six substations would be disrupted resulting in losses of about $125 million. This value is modest because delays were limited to hours because the utility expected that its network could provide the necessary resilience to avoid prolonged service interruptions.

The damage estimates for this hypothetical storm were used in conjunction with evidence from historic storms in the regions and other simulations to prepare initial recommendations for flood prevention investments in the San Francisco Area. More detailed analysis will be necessary to evaluate specific investment projects as they are developed.

5. Conclusions

Flood damage modeling has seen substantial progress over the past decade. Although, not exactly off the shelf in most cases, models are available in the United States, Europe, and Australia that provide researchers with sufficient training a means of producing flood damage estimates that can provide useful information for flood prevention mitigation policy and investment. The most serious impediment to more widespread use of these models has been the development of the data necessary to specify local damage curves and to reliably project flood likelihood and flood characteristics. Work is underway, however, in many places including New Zealand and Australia that will reduce this impediment. Better flood prevention and mitigation will be the result.

6. References

[1] Statistics from CRED (Centre for Research on the Epidemiology of Disasters).

[2] U.S. National Weather Service, Department of Commerce.

[3] Hanson, S. et.al, “A global ranking of port cities with high exposure to climate extremes,” Climatic Change (2011) 104:89-111.

[4] Insurance Council of New Zealand, “Historical Events,” http://www.icnz.org.nz

[5] According to BITRE, “Economic Costs of Natural Disasters in Australia,” Report 103, 2001, p. 13, insurance claims may represent only 10% of total damages.

[6] BITRE, “About Australia’s Regions – June 2008, Department of Infrastructure, Transport, Regional Development and Local Government, 2008.

[7] Carbone, D. and Hanson, J, “Floods: 10 of the Deadliest in Australian History,” Australian Geographic, March, 08, 2012.

[8] The earliest flood damage curve estimates have been attributed to Gilbert F. White, “Human Adjustment to Floods,” University of Chicago, Department of Geography, 1945.

[9] See for example, Walton, M. et al., “Economic Impacts on New Zealand of Climate Change Related Extreme Events. Focus on Fresh Water Floods. Report to the New Zealand Climate Change Office, 2004 and B. Jongman et al., “Comparative flood damage model assessment: towards a European Approach,” Natural Hazards and Earth System Sciences, 12, 3733-3752, 2012.

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[11] The European Union created Floodsite in 2004 to develop better data across Europe.

[12] Geoscience Australia, hazards@ga.gov.au and www.ga.gov.au/scientific-topics/hazards/risk-impact/nexis#heading-2.

[13] See for example, Tate, Eric, et al. “Uncertainty and Sensitivity Analysis of the HAZUS-MH Flood Model,” Natural Hazards Review (2014) and Bubeck, P. et al., “How reliable are projections of future flood damage?” Natural Hazards Earth Systems Science, 2011.

[14] More details regarding HAZUS may be found at: http://www.fema.gov/hazus. A useful description of model methodology can be found in Scawthorn, C. et al., 2006, “HAZUS-MH Flood Loss Estimation Methodology II, Damage and Loss Assessment.”

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[16] Army Corp of Engineers, 2011, San Francisquito Creek—Preliminary Flood Damage Analysis.

[17] Army Corp of Engineers, 2011.

[18] Welman, et. al., “Calculating Delay Propagation Multipliers for Cost-Benefit Analysis,” 2010 and M. Ball et.al, “Total Delay Impact Study”, A Comprehensive Assessment of the Costs and Impacts of Flight Delay in the United States, Final Report, October 2010 prepared for the Federal Aviation Administration.

[18] Welman, et. al, “Calculating Delay Propagation Multipliers for Cost-Benefit Analysis,” 2010 and M. Ball et.al, “Total Delay Impact Study”, A Comprehensive Assessment of the Costs and Impacts of Flight Delay in the United States, Final Report, October 2010 prepared for the Federal Aviation Administration.

[19] Hammond, M. J., et al., "Urban flood impact assessment: A state-of-the-art review," 2013.

[20] Middelmann-Fernandes, M. H. "Flood damage estimation beyond stage-damage functions: an Australian example. Journal of Flood Risk Management p. 88-96, 2010.

[21] Merz, B. et al., "Assessment of economic flood damage." Natural Hazards and Earth System Sciences,, 10, 1697-1724-2010.

[22] Nicholls, R. J. et al., "Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates." OECD Environment Working Papers, No. 1, 2007.

7. About Brattle

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