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Informing Policy Choices with Regional Estimates of Flood Risk across the United States

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ABSTRACT

With growing fiscal pressures at the Federal level and ongoing discussions about the role of the Federal government in flood management, there is a need to better understand how flood risk and resilience vary across the United States. This paper describes a national flood risk characterization tool (NFRCT) developed for the U.S. Army Corps of Engineers (USACE). The NFRCT relies on data from the Federal Emergency Management Agency (FEMA), the U.S. Census, the U.S. Geological Survey (USGS), the USACE, and other sources. FEMA's mapping of 1% annual chance exceedance (ACE) flood zones is used with the USGS National Elevation Dataset to estimate a distribution of flood depths for each flood zone. Flood zones are then overlaid with census blocks to estimate population and building exposure. Exposure is assumed to be proportional to the areal overlap of census blocks and floodzones, with the population coming from census data and the building inventory coming from FEMA's HAZUS. Finally, damages are estimated for exposed buildings using standard depth-damage functions from FEMA and USACE. Exposure and damage estimates are summed to counties and hydrologic unit code-8 watersheds for comparing risk across different areas of the United States.

INTRODUCTION

Floods are known to be the most damaging natural disasters in the United States (Downton and Pielke 2005, Gall et al. 2011). The Federal Government plays a large role in managing flood risk, spending billions of dollars each year on programs to reduce flood risk, including building and maintaining flood control infrastructure, mapping areas prone to flooding, subsidizing flood insurance, and providing grants to localities to implement local risk management projects (Shabman and Scodari 2014). Further, in recent years large flood disasters have resulted in repeated emergency appropriations from Congress. With growing fiscal pressures at the Federal level and ongoing discussions about the role of the Federal Government in flood management (see Shabman and Scodari 2014), there is a need to better understand how flood risk and resilience vary across the United States so that Federal agencies and others can make risk-based decisions about policy, investments, and other activities.

We do not currently have a comprehensive understanding of flood risk in the United States.

Historical data on flood damages[1] are reported to be relatively reliable at high levels of aggregation, but less reliable for smaller regions or individual events (Downton and Pielke 2005). The historical data do not provide a thorough understanding of current and future risks because of problems with the data, as well as the fact that risk is likely changing over time due to development, climate, and other factors. For a modeled estimate of flood risk, the Federal Emergency Management Agency (FEMA) used a Level 1 analysis in HAZUS-MH to estimate average annual loss around the United States.[2] The Level 1 analysis has several weaknesses but the most significant is its inability to account for the effects of levees, dams, and other infrastructure on the aerial extent of inundation.

To develop a more a robust estimate of flood risk in the United States, the Institute for Water Resources (IWR) funded work to develop a National Flood Risk Characterization Tool (NFRCT) in order to meet two related objectives. The first objective was simply to test the feasibility of developing a tool that could identify areas of relatively high flood risk using national-level and publically available data. The second objective was to provide the U.S. Army Corps of Engineers (USACE) with an easy-to-use method to identify areas facing potentially high relative flood risk in order to support strategic discussions among leadership about agency priorities for flood risk management investments (e.g., new planning studies, construction of new infrastructure, operation and maintenance of existing infrastructure).

The NFRCT relies on a standard set of flood risk concepts and terms (see Shabman et al. 2014), including:

- Flood Hazard – The predicted probability distribution of flood water depths for different locations within a floodplain expected from all possible floods. In the NFRCT, mapping for the 1% annual chance exceedance floods is used as a proxy for overall flood hazard.
- Flood Exposure – The potential for people and assets to come into direct contact with flood water as a result of their location in a floodplain.
- Vulnerability – The characteristics of people and assets that affect the likelihood that they will realize adverse consequences from exposure to the flood hazard.
- Flood Damage – The adverse consequences to people and assets expected (or realized) from their exposure and vulnerability to the flood hazard or a portion of the hazard (i.e., one or more potential floods).
- Flood Risk – The likelihood and adverse consequences of flooding. Flood risk for assets and people at any location in a floodplain is a function of flood hazard at that location and their exposure and vulnerability to the flood hazard.

The NFRCT addresses each element of flood risk listed above using publicly available datasets and a series of computations to estimate flood depths, exposure, and damages. The results provide indicators of relative flood risk around the United States.

DATA

The NFRCT incorporates data from multiple Federal agencies in order to estimate flood risk. Table 1 lists the key datasets and summarizes how they are used in the NFRCT. The National Flood Hazard Layer (NFHL) includes mapping for the 1% annual chance exceedance (ACE) and 0.2% ACE floods; these are used as proxies for hazard in the estimation of overall risk.

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[1]See data from the NWS at http://www.flooddamagedata.org/ and http://www.flooddamagedata.org/.

[2]See https://arcg.is/0ye0H1.

Table 1. Summary of datasets used for the NFRCT.

Dataset	Source	Use in NFRCT
National Flood Hazard Layer	FEMA	Used as the basis for flood hazard, delineates areas prone to 1% and 0.2% ACE floods, and used to determine flood depth distributions for flood consequence calculations
National Elevation Dataset	USGS	Used to determine water surface elevation and flood depth distributions
Watershed Boundaries	NRCS	Used to aggregate and display most NFRCT data on flood risk, exposure, damages, etc.
National Land Cover Dataset	USGS	Used to determine developed land areas for locating population and assets
Population and Demographics	U.S. Census Bureau	Used to compute population exposure to potential flood, as well as for demographics of vulnerability metrics
General Building Stock	FEMA	Used for asset inventories and determining economic value to calculate exposure and damages
Depth-Damage Relationships	USACE and FEMA	Used to compute flood damages to certain residential buildings and vehicles as a function of inundation depth

USGS: U.S. Geological Survey, NRCS: Natural Resources Conservation Services; USACE: U.S. Army Corps of Engineers.

COMPUTATIONAL METHODS

Estimating Flood Depths

Data from the NFHL were processed using ArcGIS *Repair Geometry.* In addition, flood zone boundaries were simplified so that the minimum distance between adjacent points along each boundary was 0.5 meters. This speeds the computation of flood depths for the NFRCT. In addition, interior lines (e.g., boundaries of the floodway) are removed so that the resulting shapefiles define only the outer boundary of each floodzone (see Figure 1).

Figure 1. Correcting flood zone polygons to eliminate interior lines.

The NFRCT uses the National Elevation Dataset (NED) to estimate depths within each floodzone. First, the NED is processed to smooth the gridded elevation data into a more continuous dataset. Smoothing is accomplished using Neighbor-Based Interpolation (NBI; Firlie 2007). The smoothed result can be seen in Figure 2.

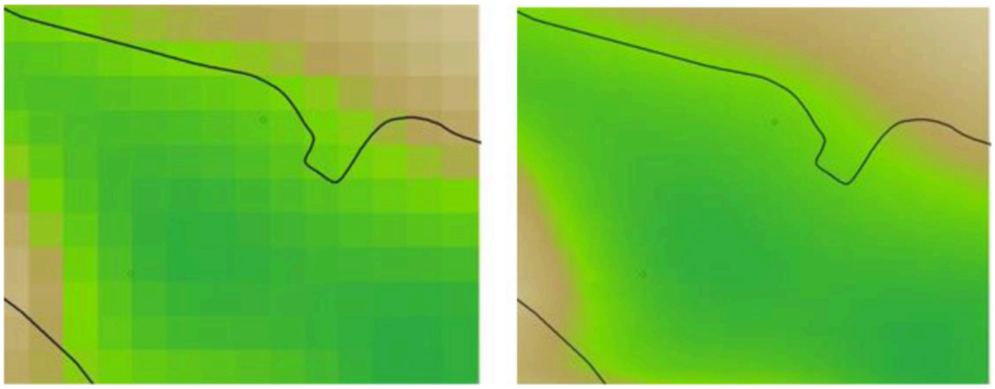

Figure 2. Impact of neighbor-based interpolation on NED.

Floodzone data are then overlaid with the smoothed NED. Along the perimeter of each flood zone, which include the perimeters of any internal holes (e.g., highpoints within the floodplain), the depth of the flood is assumed to be zero. The NFRCT calculates depths based on elevation differences. We can thus obtain elevation values for every point around the perimeter of each floodzone. All of these points are stored in a mesh structure that allows for quick interpolation. Elevation points within the interior of a flood zone polygon requires identification of the nearest neighbors in the perimeter mesh structure. Elevations of the neighboring points are averaged using the NBI technique (Firlie 2007) to estimate the water surface elevation at the point of interest. The NED ground elevation at the point of interest is subtracted from the weighted average of the perimeter neighbors and the result is the estimated flood depth at that point. In the case of coastal flood zones, Base Flood Elevation (BFE) lines, which are provided in the NFHL for coastal areas, are used instead of the perimeter points in order to account for wave height. The water surface height for these zones is then calculated as the weighted average of any nearby BFEs.

To illustrate graphically, Figure 3 shows a target point in the interior of the flood zone polygon at which the flood depth is to be calculated. It also shows many perimeter points that comprise the perimeter of the flood zone. As noted earlier, these perimeter points are assumed to have a flood depth of zero. The black lines show the mesh structure containing the perimeter points. The larger points along the perimeter are determined to be the nearest neighbors of the target point within the floodzone. Ground elevation at the target point is retrieved from the smoothed NED. The depth at the target point is estimated as the difference between the ground elevation at the target point and the nearest neighbor average of perimeter elevations. The NFRCT randomly samples points from the interior of each floodzone and estimates depth for each sampled point using the procedure described above. Each sampled point is defined as either developed or undeveloped using the National Land Cover Dataset (NLCD)[3]; this information in used in the exposure calculation (described below).

[3]There are four classes of developed land in the NLCD: (1) Developed, Open Space; (2) Developed, Medium Intensity; (3) Developed, Low Intensity; and (4) Developed, High Intensity. These are lumped into one category for the purposes of NFRCT. All other NLCD classes are lumped into an undeveloped category for the NFRCT.

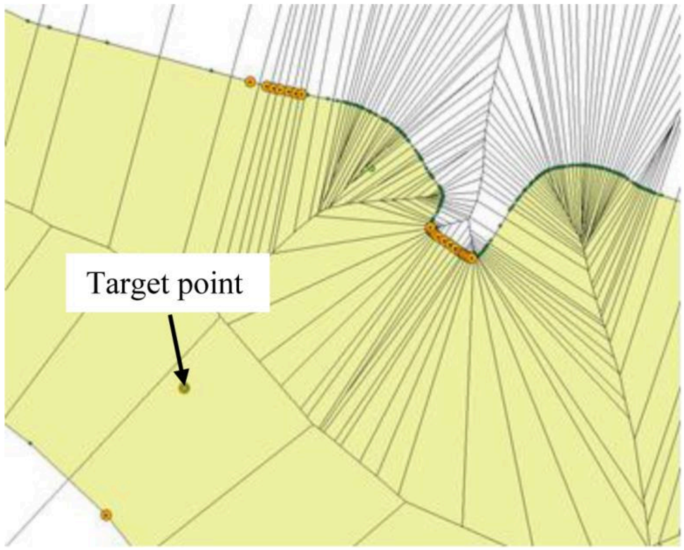

Figure 3. Target point, perimeter points, and mesh structure.

Spatial Aggregation

The three key datasets for NFRCT computations are provided with three different spatial geometries: flood zone polygons in the NFHL, Census blocks (for population and built assets), and hydrologic unit code (HUC)-8 watersheds (for reporting and displaying final results). In order to determine population and asset exposure to floods and then aggregate those results by watershed, a correspondence between those three geometries must be created. The map in Figure 4 shows a sample of overlap and intersection between flood zones, Census blocks, and HUC-8 watersheds. Many Census blocks are shown (grey boundaries) and the flood zone is shown in pink. Some blocks are split by the flood zone boundary, others are split by the HUC-8 boundary, and some are split by both. The overlay of these three geometries creates a new set of spatial units for flood exposure and consequence calculations.

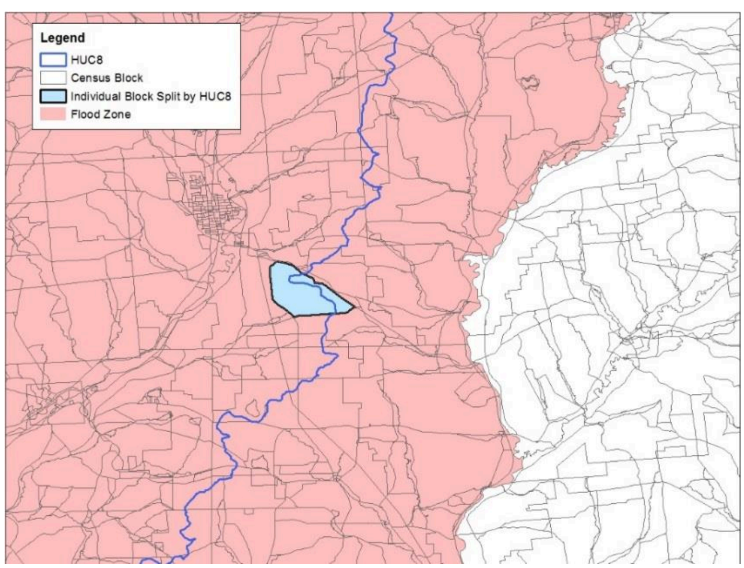

Figure 4. Flood zone, Census blocks, and HUC-8 overlap.

Flood Depth Distributions

In order to estimate population, asset exposure, and asset damages, estimated flood depths are apportioned to the intersections of floodzones, Census blocks, and HUC-8 watersheds. For most intersections, this results in flood depth estimates for hundreds of sampled points. The sampled points are used to calculate percentiles of flood depths of for each intersection (see Table 2 for a sample). Only the depth data and percentiles for points that fall in NLCD developed classes are used in calculating exposure and damages. For simplicity, the NFRCT retains and uses odd percentiles depths (i.e., the 1st percentile depth, the 3rd percentile depth, and so on).

Table 2. Sample intersection of flood zone, HUC-8 watersheds, and Census blocks, with sample of the depth distributions calculated for the NFRCT.

	DRFIM 29137C, Zone A							
				Depth distribution percentiles (feet)				
Census block ID	HUC-8	Census Block area (m^2)	Flood zone/ Census block/HUC intersection area (m^2)	P1	P11	P51	P91	P99
291379602001002	07110005	14,239	7,822	0.4	1.9	5.7	10.5	11.7
291379602001043	07110005	206,859	28,543	0.1	1.6	5.3	17.3	28.4
291379603003112	07110006	38,269	26,490	0	1.3	3	5.1	6.1
291379602002004	07110006	41,162	30,667	2.2	7.2	15.9	27.5	31.4
291379601003404	07110007	371,860	86,299	12.6	25.6	28.1	28.9	29.2

Flood Exposure

Once flood depths are estimated and apportioned to each intersection, the population and asset exposure are estimated. As noted above, the NLCD is used to inform the exposure calculation. We assume that people and buildings are uniformly distributed throughout portions of Census blocks that fall in one of the NLCD's developed land classes. Population data come from the U.S. Census; building counts and values come from FEMA's General Building Stock inventory (FEMA 2009); and vehicle counts and values come from the HAZUS Vehicle Location Estimation System (FEMA 2009).

Assuming the even spatial distribution of people and assets, we use the percentage of the developed portion of a Census block that is intersected by a floodzone to estimate exposure. Exposure is defined as:

$$E_{ijk} = \left(\frac{\bar{I}_{ijk}}{Bdev_i} \right) \times T_i$$

where:

E_{ijk} is the exposure in the intersection of Census block i, floodzone j, and HUC k, expressed as the number of people

$\bar{I}_{ijk}$ is the area of the intersection of Census block i, floodzone j, and HUC k (see Figure 5).

$Bdev_i$ is the area of the portion of Census block i that falls in one of the four classes of developed land in the NLCD

T_i is the total population for Census Block i.

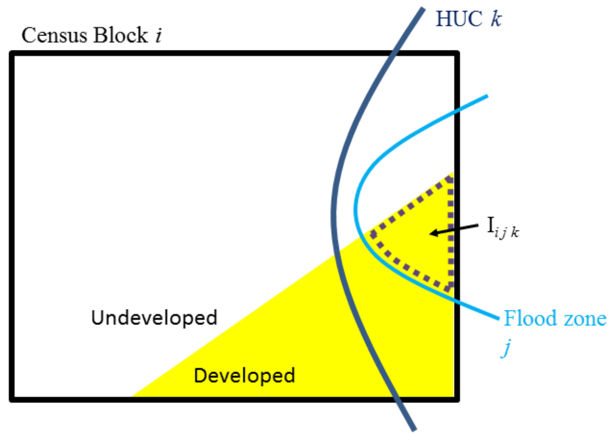

Figure 5. Schematic of the intersection between Census blocks, flood zones, HUCs, and NLCD developed land classes.

For each intersection, the exposure calculations are used to estimate population exposure and asset exposure. Population exposure represents the number of people that would be exposed to the 1% ACE floods (and, where data are available, the 0.2% ACE floods). Asset exposure includes both the number of assets (e.g., buildings or vehicles) and the aggregate value of assets (in dollars) that would be exposed to the 1% ACE floods (and, where data are available, to the 0.2% ACE floods).

Note that a Census block can have more than one intersection if it is overlapped by more than one floodzone or if the floodzone-block intersection is bisected by an HUC boundary. In this case, the exposure in the block would be calculated as the sum of exposure across multiple intersections.

Flood Damage

Damages are estimated as a function of asset exposure and depths within each intersection. The damage estimate is performed using standard depth damage functions from FEMA (2009) and USACE (2000, 2003). The NFRCT assesses flood damages for (1) residential buildings and contents, (2) nonresidential buildings and contents, and (3) vehicles. There are separate depth-damage functions for different types of buildings (e.g., one-story houses with basements, two- or more story houses with basements, mobile homes), contents of buildings, and vehicles. FEMA's General Building Stock inventory includes counts and aggregate values for each type of building and contents by Census block. The exposure rates described above are assumed to apply uniformly to each category of building (i.e., each type of building is assumed to be evenly distributed across developed portions of Census blocks). The same assumption is made for the estimate of vehicle exposure.

Depth damage functions indicate the percentage loss as a function of depth of exposure (see Figure 6). Since the exposure analysis described above is applied to aggregate building and vehicle counts and value within Census blocks, the damage calculation is applied in aggregate as well. In other words, depth-damage functions are not applied to individual buildings or vehicles, but are applied to the aggregate value of exposed buildings or vehicles in a block.

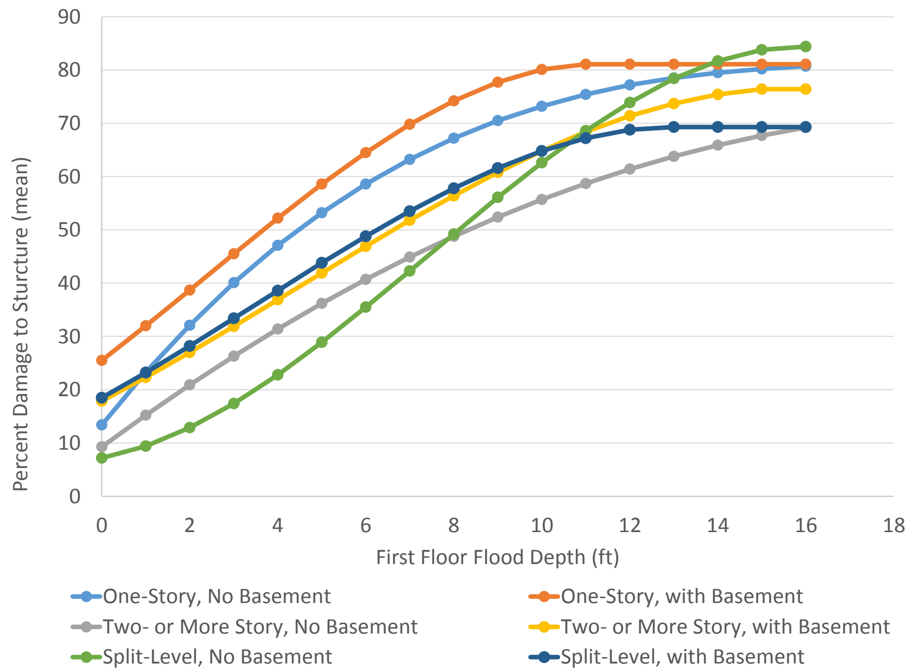

Figure 6. Selected depth-damage functions used for the NFRCT. Sources: USACE (2000, 2003), FEMA (2009).

Damages are estimated as follows:

$$D_{ijk} = \sum_{x\,m} d_m\left(H_{xijk}\right) \times p_x \times E_{ijk}$$

where:

D_{ijk} is the estimated asset damage for the intersection of Census block i, floodzone j, and HUC k

d_m is the damage function for asset type m (see examples in Figure 6)

H_{xijk} is the xth percentile depth for the intersection of Census block i, floodzone j, and HUC k, expressed in feet

E_{ijk} is the asset exposure (in terms of total dollar value) for the intersection of Census block i, floodzone j, and HUC k

p_x is percentile increment from X-1 to X, expressed as a fraction.

The function d_m (H_{xijk}) results in a percentage loss for each percentile of the depth distribution within the intersection. Multiplying this percent loss by the exposed building value results in an estimate of dollar loss. Since we assume that buildings and aggregate value are evenly distributed across developed areas of Census blocks, we assume uniform exposure to the distribution of flood depths. Further, the model uses odd percentile depths so exactly 1% of the total building value is exposed to the first percentile depth, exactly 2% of building value is exposed to the third percentile depth, and so on.

For buildings, the damage function requires an estimate of depth of exposure relative to first floor elevation. First floor elevations are obtained for percentages of Census block level inventories of building types using data from FEMA's HAZUS-MH (FEMA 2009). HAZUS-MH provides first floor elevations for different building types based on whether the buildings predate the National Flood Insurance Program. In addition, HAZUS-MH provides estimates of the distribution of building types by state; the state level percentages are applied to all blocks within each state to determine first floor elevations by building type for each Census block.

Summing Results to Watersheds

Using the intersection of blocks, floodzones, and watersheds, we can sum exposure and damages to HUC-8 watersheds. Damage in HUC-8 k is defined as:

$$D_k = \sum_{ij} D_{ijk}$$

where D_{ijk} is the estimated damage for all asset types within the intersection of block i, floodzone j, and HUC k.

Since HUC watersheds are hierarchical, results can be summed to larger watersheds for larger regional comparisons.

RESULTS

The NFRCT presents flood risk characterization data on a map interface and via detailed reports (see Figure 7). Users can select to view results by different levels of HUC watersheds and can also select to filter results based on various metrics (e.g., show only watersheds in the top 10% of damages). Individual reports provide details for one or more user-selected watersheds.

Results for the entire nation suggest that over 13 million people live in 1% ACE floodzones and could be potentially exposed to 1% ACE floods. Expected damages across all 1% ACE floodzones totals over $540 billion. In the HUC-8 with the highest levels of flood risk (the Southeast Coast of Florida), the potential population exposure across all of the 1% ACE floodzones is nearly 1.5 million and expected damages exceed $50 billion. These numbers represent total risk across all 1% ACE floodzones in southeast Florida. However, the probability of the entire southeast coast of Florida experiencing a 1% ACE flood at the same time is unknown.

LIMITATIONS

Although the NFRCT makes use of the most up-to-date information available at a national level on flood hazard and exposure, it still has significant limitations. These are:

1. The NFHL includes floodplain boundaries associated with only the 1% annual chance floods and, less commonly, the 0.2% annual chance floods. Therefore, the NFRCT uses the risk associated with these flood events as a proxy for overall flood risk for a geographic area. Assessing risk with a limited description of the distribution of potential floods may provide biased results (see Ward et al. 2011). Therefore, the information provided by the NFRCT may not be appropriate for characterizing the absolute flood risk facing a single geographic area and should be used primarily for evaluating relative flood risk across watersheds.
2. The indicators of flood risk provided by the NFRCT are only as good as the underlying flood zone boundaries from digital flood insurance rating maps (DFIRMs). The flood zone boundaries included in the NFHL are estimated based on several different types of studies. In most cases, detailed hydrologic and hydraulic modeling were conducted and the flood zone boundaries are likely quite accurate. In other cases, the boundaries are based on older and much less-precise methods.
3. Flooding is extremely site-specific, and the location of a building within a flood zone can mean the difference between exposure to low flood depths and little or no damage, and