The Cost of Coastal Storm Surge Damage Reduction

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I. Introduction

Hurricanes cause billions of dollars in property damage along the Atlantic and Gulf coasts of the United States [3]. After accounting for changes in purchasing power, population and wealth, recent studies find that average annual hurricane damage in the US for the 73 years ending in 1997 is $5.2 billion [8]; furthermore, increasing coastal development exacerbates potential damage [9]. Although the extreme rainfall associated with tropical weather causes upstream flood damage, as evidenced by the recent flooding in North Carolina due to hurricane Floyd [5], storm surge flooding is of greater concern for coastal property owners.

Coastal building codes are designed to protect property against storm surge flooding. However, some property owners make improvements beyond code to provide added protection. These improvements include house elevation on fill or pilings, levee and floodwall construction and house relocation. Given recent hurricane strikes in Wilmington, NC - Bertha, Fran, Bonnie, Dennis and Floyd - we investigate the costs of storm surge mitigation for individual property owners in that region.

We find: (1) least-cost improvements vary with storm surge depth, foundation type, and new versus retrofit construction; (2) the incremental benefits of structural improvements, in terms of damage reduction, are increasing in improvement expenditures; and (3) the least-cost response to a given storm surge level is to either purchase no structural defenses (beyond building code requirements) or to purchase enough structural defenses to prevent all damage--"all-or-nothing" purchase behavior. Furthermore, we show that hurricane strikes *at particular locations* are such low probability events that the expected benefits from defensive expenditures (beyond building codes) may not justify even least-cost improvements.

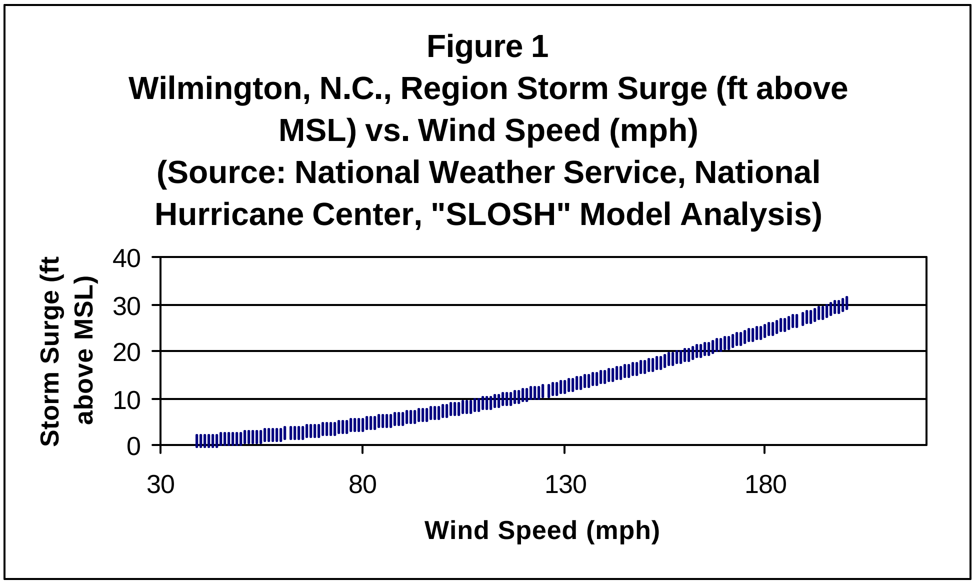
II. Storm Surge and Flood Depth per Hurricane Category

We consider a new residential structure located in Wilmington, NC, that conforms to 1999 building codes. The 2,150 sq. ft. (1 sq. ft. = 0.0929 sq. m.), one-story, wood frame home with vinyl siding is valued at $140,000. The structure includes 3 bedrooms, 2 bathrooms, and a 2-car garage. The home's contents are valued at 70% of structure value, or $98,000. The property is located within five miles of the ocean, but is far enough inland to escape direct wave action in the event of storm surge flooding. We assume that the structure rests on a 3-foot (1 ft. = 0.3048 m.) crawl space. This home is typical of new construction in the area.

The house sustains potential flood damage as a result of storm surge--extreme coastal tide levels associated with hurricanes. Specifically, we define s*torm surge* as the increase in mean water level above mean sea level (MSL). Expected storm surge levels are closely associated with hurricane wind speed intensity. The National Weather Service (NWS) Sea, Lake and Overland Surges from Hurricanes (SLOSH) model [4], computes the approximate relationship between tropical weather wind speed and storm surge. The SLOSH model relationship, calibrated for Wilmington, NC, is given by:

(1) $$SS = -0.47246 + 0.000764 \cdot (WS)^2,$$

where SS is Storm Surge measured in feet above MSL and WS is maximum sustained wind speed measured in miles per hour (1 mph = 1.609 kph). This relationship is depicted in Figure 1.



We use the Saffir-Simpson scale to categorize tropical weather intensity from tropical storm to category 5 hurricane based on maximum sustained wind speeds. Using the SLOSH model relationship in equation (1), Table 1 shows also the approximate storm surge depth at the study location for each hurricane category. Storm surges are determined using the midpoint wind speed of each category.

Table 1 – Hurricane Wind Speed Categories, Associated Storm Surges and Flood Depths for the Case Study Location

Saffir-Simpson Storm Category	Max. Sustained Wind Speed Ranges	Midpoint of Wind Speed Range (mph)	SLOSH Storm Surge (ft above MSL)	Flood Depth (ft)	Flood Depth minus ZDE* (ft)
Tropical Storm	39-73mph	56	1.9	0	0
Cat 1	74-95mph	84.5	5	0	0
Cat 2	96-110mph	103	7.6	0	0
Cat 3	111-130mph	120.5	10.6	1.6	0
Cat 4	131-154mph	143	15.2	6.2	3.2
Cat 5	155+mph	175	22.9	13.9	10.9

*Assumes Zero Damage Elevation (ZDE) is 12 ft above Mean Sea Level (MSL)

Flood depth, FD, is defined as the storm surge level minus the location's ground elevation above MSL. We assume that the ground elevation of the property is nine feet above MSL. This elevation is representative of several important locations in the region, including the downtown Wilmington waterfront, downtown Carolina Beach and sections of downtown Wrightsville Beach. The water level experienced *within a structure* depends not only on ground elevation, but also on the amount by which the structure is raised above the ground. We define the *zero damage elevation* (ZDE) as the elevation above MSL at which floodwaters first begin to enter the structure (USCE 1993). ZDE is equal to the elevation of the ground floor of the structure, and we assume that any outdoor utilities (e.g., heat pump) are also elevated to ZDE. As the structure is on a 3-foot crawl space, ZDE is 12 feet (9-foot ground elevation above MSL plus the 3-foot crawl space). Consequently, a 15.2 foot storm surge, for a Category 4 storm evaluated at the midpoint wind speed, produces a 6.2 foot flood depth above ground elevation (15.2 foot storm surge - 9 foot ground elevation), but only a 3.2 foot flood depth *above ZDE* (15.2 foot storm surge - 12 foot ZDE). Table 1 provides flood depth and flood depth above ZDE for each hurricane category. Note that water does not enter the example structure for storms below category 4.

III. Storm Surge Damage

Absent structural improvements beyond building code requirements, both the structure and its contents suffer flood damage in the event of a "Cat 4" or a "Cat 5" hurricane. As a given flood depth typically causes a greater percentage loss to contents than to the structure itself, we develop separate relationships for both structure and contents damage. The estimated relationships are based on Federal Emergency Management Agency (FEMA) Actuarial

Information System claims data [10] and are represented by:

(2) PDS = exp(-1.88 + 0.75 · ln(SS - ZDE))/(1 + exp(-1.88 + 0.75 · ln(SS - ZDE))) and

(3) PDC = exp(-1.62 + 0.86 · ln(SS - ZDE))/(1 + exp(-1.62 + 0.86 · ln(SS - ZDE))),

where PDS is damage to the *structure* as a percentage of the structure's value (assuming a one-story structure) and PDC is damage to the structure's *contents* as a percentage of contents value. These relationships are illustrated in Figures 2a and 2b. Both structure and content damages are increasing at a decreasing rate; initial flood intrusion is the most costly.

Figure 2a
Structural Damage As a Fraction of Structure Value vs. Flood Depth Above Zero Damage Elevation

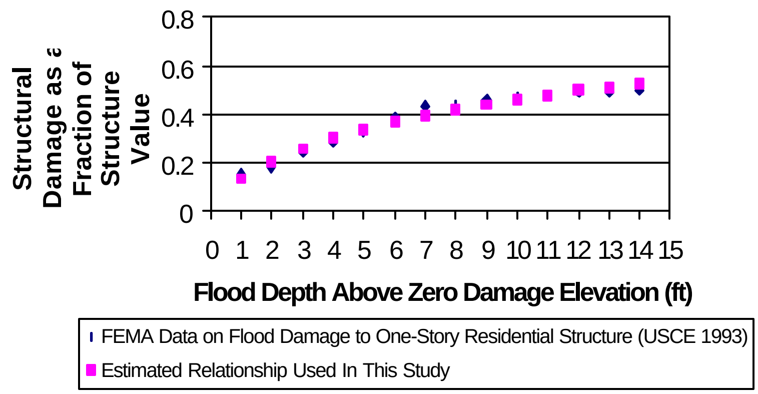
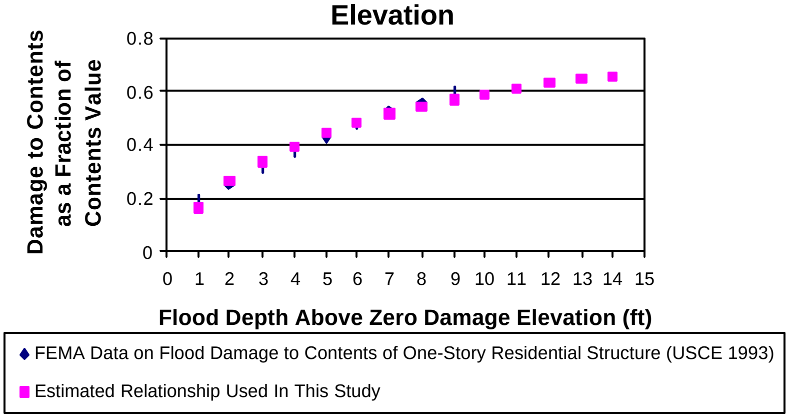


Figure 2b
Damage to Contents As a Fraction of Contents Value vs. Flood Depth Above Zero Damage Elevation



Using equation (2), a category 4 hurricane (3.2-foot flood depth above ZDE) causes approximate damage to the structure equal to 26.74% of the structure's value, or $37,436 (0.2674 times $140,000), and damage to contents equal to 34.99% of contents value, or $34,290, for total damage of $71,726. Using equation (3), a category 5 hurricane (10.9-foot flood depth above ZDE) causes approximate damage to the structure equal to 47.79% of the structure's value or $66,906 and damage to contents equal to 60.69% of contents value, or $59,476, for a total of $126,382.

IV. Damage Reduction Costs

We rely on existing research [10, 11, 12, 2] to identify a range of flood damage-reducing activities. These activities include house relocation, house elevation on fill or pilings, and levee and floodwall construction. This section outlines the assumptions used to estimate implementation costs for each activity. Since costs depend on foundation type, we present also the implementation costs for a slab foundation. Costs are generally higher for slab than for crawl-space foundations.

House Relocation

Given a structure 33 ft wide and 66 ft long, or 2,150 sq. ft., and assuming a relocation site within five miles, the relocation cost for a home built upon a crawl space foundation is $27/sq. ft., or $51/sq.ft. for a slab foundation [2]. This cost includes a new foundation, structure installation, and utilities connection at the new site. It does not include land costs. We assume that new land costs are covered by the sale of the vacated land.

House Elevation on Pilings

The cost of raising a crawl space house on pilings is $17/sq. ft. for the first two feet of elevation, plus $0.75/sq. ft.for each additional foot of elevation, plus an additional $1.00/sq. ft. for each additional foot of elevation beyond 8 feet [2]. Costs include utility elevation and staircase extension. The cost of raising a slab foundation house on pilings is $47/sq. ft. for the first two feet of elevation, plus $0.75/sq. ft. for each additional foot of elevation, plus an additional $1.00/sq. ft. for each additional foot of elevation beyond 8 feet [2]. This cost assumes that the slab remains attached after elevation.

Levee Construction

We consider a levee composed of compacted earth with 1ft.-thick riprap on the water side [2]. We assume a ten-foot desired clearance between the house and the base of the levee, a maximum levee height of 6 ft (due to hydrostatic pressure constraints), a five-foot wide levee top and a 2.5:1 side slope ratio. Levee wall cost is $37.00 per foot of center-line circumference for a 2-foot high levee, $69.00 per foot of circumference for a 4-foot high levee and $115 per foot of circumference for a 6-foot high levee. The cost of riprap is $1.15 per cubic foot. We assume one, 12-ft. opening (with removable barrier) in the levee at a cost of $73/sq. ft. of opening base area.

Floodwalls

We consider a concrete or masonry floodwall one-foot in width [2]. We assume a ten-foot desired clearance between the house and the base of the floodwall and a maximum floodwall height of 4 ft (due to hydrostatic pressure constraints). Its cost is $85.00 per foot of center-line circumference for a 2-foot high floodwall and $124.00 per foot of circumference for a 4-foot high floodwall. We assume one, 12-ft. opening (with removable barrier) in the floodwall at a cost of $73.00/sq. ft. of opening base area.

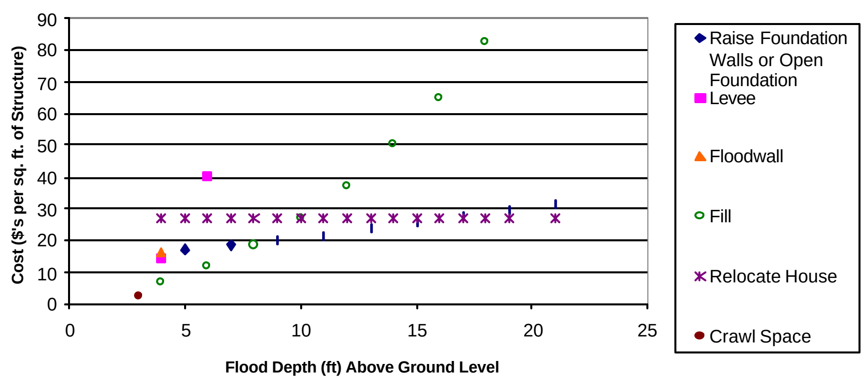
Elevation on Fill

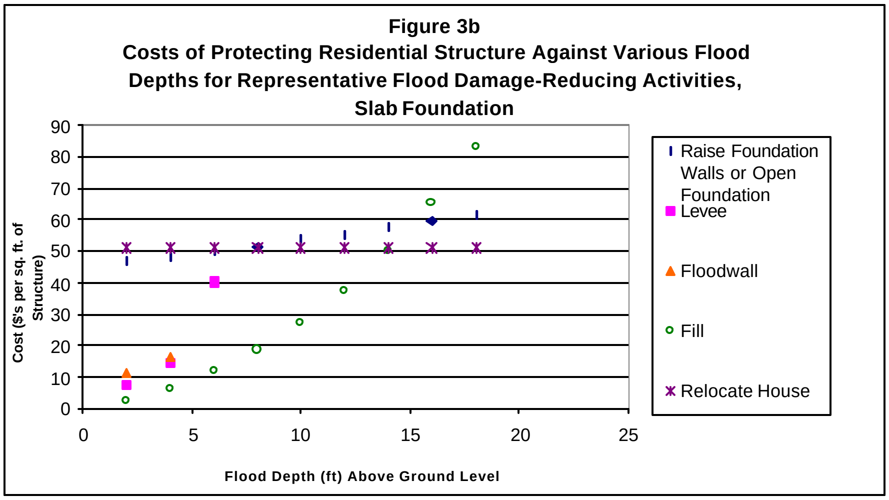
We consider elevation on fill prior to home construction [10]. We assume a rectangular fill area with a 3:1 slope ratio. We further assume ten feet of clearance between the top edge of the rectangular fill and the structure. The cost of delivered fill material is $10/cubic yard. The cost of grading and compaction is $5/cubic yard.

V. Least Cost Damage Reduction

Property owners choose between the various structural improvements to achieve a given level of flood protection. A flood depth of 6.2 feet above ground level caused by a category 4 hurricane is excluded from the structure by fill dirt at a cost of $11.87/sq. ft. or by elevating the house for approximately $18/sq. ft.. Similar cost comparisons can be made across activities for other flood depths. Figures 3a and 3b facilitate comparisons by foundation type.

Figure 3a
Costs of Protecting Residential Structure Against Various Flood Depths for Representative Flood Damage-Reducing Activities, Crawl Space Foundation





The bottom envelope of points in each figure gives *least-cost* activities by flood depth. The type of least-cost activity varies by flood depth and foundation type. Least-cost activities become more expensive as flood depth increases.

The width and height of many structures relative to utility line height and roadway width restrict off-site relocation activities. We assume that off-site house relocation is not a feasible option for the case study structure. In addition, we assume that *existing* structures, including our representative home, cannot be raised using fill dirt. Thus, the least-cost activities for our crawl space home are represented by the bottom envelope of points in Figure 3a, with the points for activities "Fill" and "Relocate House" excluded.

VI. Marginal Analysis of Flood Damage Reduction and "All or Nothing" Behavior

A *flood damage-reduction function* is the relationship between flood damage (total of both structural damage and damage to contents) and expenditures on least-cost flood damage-reducing activities. Data in Table 1 indicate that the representative home suffers no flooding (and hence no flood damage) for tropical storms and hurricane categories 1 to 3. Flood damage-reduction functions for hurricane categories 4 and 5 are illustrated in Figures 4a and 4b and are approximated by:

(4) $D^f_4 = MAX[0, 33.1093 + 0.002572 \cdot (1 - exp(0.5115 \cdot c^f))]$, and

(5) $D^f_5 = MAX[0, 59.0546 + 0.15183 \cdot (1 - exp(0.235 \cdot c^f))]$,

where D^f_i is flood damage in dollars per sq. ft. of structure for hurricane intensity i, and c^f is least-cost expenditures on flood defensive measures in dollars per sq. ft. of structure.

Figure 4a
Flood Damage vs. Flood Defensive Expenditures for Hurricane Category 4

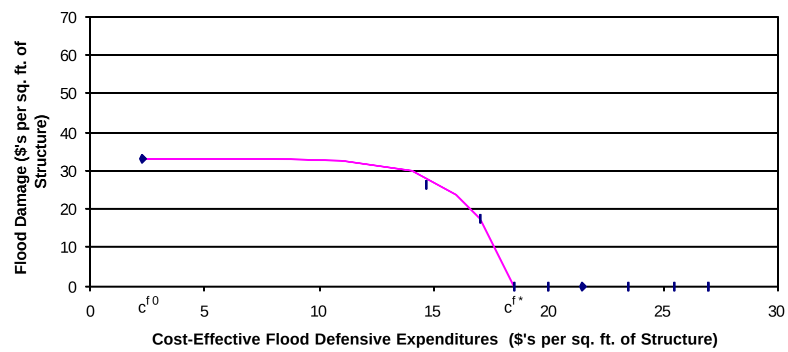
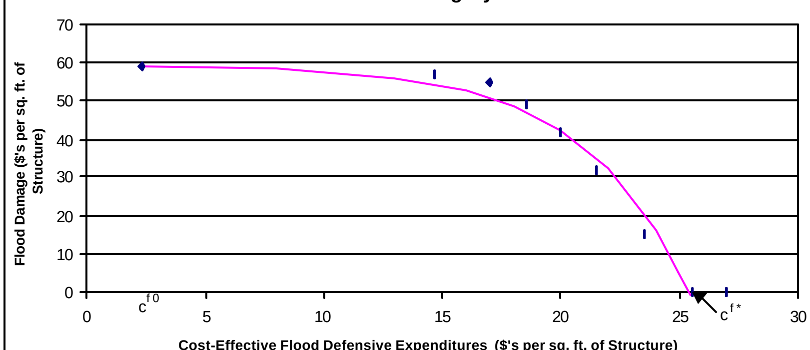


Figure 4b
Flood Damage vs. Flood Defensive Expenditures for Hurricane Category 5



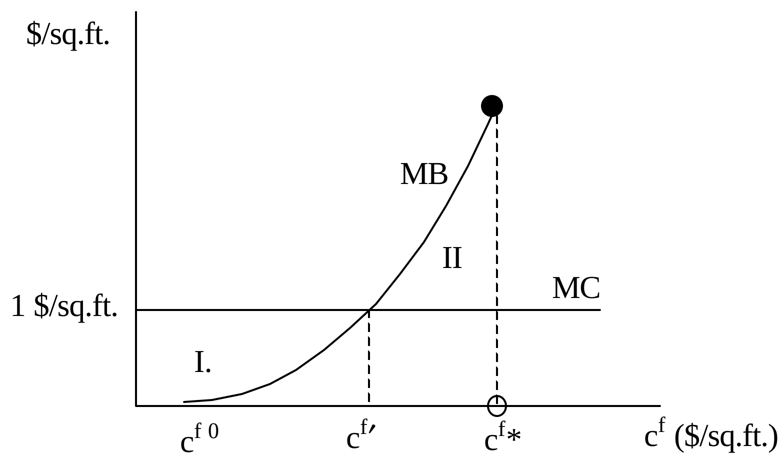
Flood damage for each hurricane category is decreasing and concave in least-cost flood defense expenditures beyond some lower threshold of expenditures, c^{f0}. This is the case because elevating a house by a small amount protects only the *upper* portion of the house, where relatively little of the value of the house is located. Elevating a house by a large amount protects the *lower* portion of the house, where most of the value of the single-story house (i.e., most appliances, furniture, clothes, etc.) is located.

Beyond some *upper* threshold of expenditures, c^{f*}, further expenditures yield no additional damage reduction. From equations (4) and (5), these upper threshold values are \$18.50/sq. ft. and \$25.38/sq. ft. for categories 4 and 5, respectively. In other words, if the owner spends \$39,775 (\$18.50/sq. ft. · 2,150 sq. ft.), he prevents all damage from a hurricane category 4 storm surge. Expenditures of \$54,567 prevent all damage from a category 5 storm surge.

Flood damage reduction is a *benefit* of structural improvement expenditure. For a category 4 hurricane, the m*arginal (incremental) gross benefit* (MB) of structural improvement expenditure is given by the slope of the function illustrated in Figure 4a (i.e., MB is the derivative of $D^f{}_4$). This slope is graphed against *least-cost* structural improvement expenditures, c^f, in Figure 5. As least-cost expenditures increase, marginal benefits are initially small but then increase. In other words, the accelerating reduction in flood damage illustrated in Figure 4a is reflected by increasing marginal benefits in Figure 5. At expenditure level c^{f*}, the structure is fully protected against a category 4 storm surge; the marginal benefit of further expenditures falls to zero. In Figure 5, the *total (cumulative) gross benefit* of any given level of least-cost expenditures c^f is calculated as the area under the marginal benefit curve from zero to c^f.

The marginal cost of least-cost structural improvements is represented by a horizontal line at \$1/ sq. ft.. (The marginal cost of an additional \$1/sq. ft. of structural improvements is simply \$1). The *total (cumulative) cost* of any given level of c^f is calculated as the area under the marginal cost curve from zero to c^f.

Figure 5.



For the purpose of illustration, assume that an owner expects a category 4 hurricane strike to occur with probability 1 (this assumption will be relaxed in the next section). The owner weighs the marginal benefits of improvements versus the marginal costs to determine the level of expenditures that provides the highest *net* benefit. Improvement expenditures in the range $(0, c^{f\prime})$ are clearly not cost-effective, as MB is less than MC throughout the range, implying that the incremental benefits of expenditures are less than the incremental costs throughout this range. In this range, if the owner makes defense expenditures of $c^{f\prime}$, he incurs a *net* cost equal to Area I in Figure 5. Thus, the owner prefers zero expenditure to any other expenditure level in the range $(0, c^{f\prime})$.

Notice next that MB increasingly exceeds MC over expenditure range $(c^{f\prime}, c^{f*})$; hence, the owner prefers an expenditure level of c^{f*} to any other expenditure level in this range. The net benefit of expenditures from $c^{f\prime}$ to c^{f*} is given by Area II. As the owner prefers zero expenditures in the range $(0, c^{f\prime})$, and as the owner prefers c^{f*} expenditures in the range $(c^{f\prime}, c^{f*})$, he chooses between only these two expenditure levels; the choice is “all or nothing.” If Area I is greater than Area II, then zero expenditure is best. If Area I is less than Area II, then expenditure equal to c^f* is best. For example, as a category 4 hurricane causes $71,726 in total damages, a zero expenditure level results in a net cost of $71,726. If expenditures equal to c^f* are selected, these hurricane damages are reduced to zero. Since c^f* is $18.50/sq. ft. for a category 4 storm, the total cost of implementing c^f* for this storm category is $39,775 ($18.50/sq. ft. · 2,150 sq. ft.). The net benefit of implementing c^f* is a cost reduction of $31,951 ($71,726 - $39,775), i.e., instead of incurring $71,726 in damages, the owner spends $39,775 to prevent the damages, a reduction in cost of $31,951. Thus, assuming that a category 4 hurricane occurs with probability 1, expenditure level c^f* (or $18.50/sq. ft.) is chosen. Assuming that a category 5 hurricane occurs with probability 1, a similar analysis shows that the full defense option c^f* of $25.38/sq. ft. is chosen. A total cost of $54,567 prevents damages of $126,382, for a net benefit of $71,815 ($126,382 - $54,567).

VI. Expected Net Benefit Analysis

We now investigate purchase decisions under realistic strike probabilities. Table 2 provides National Weather Service's (NWS) HURISK model estimates of tropical weather strike probabilities and associated wind speeds for Wilmington, NC [6, 7]. These estimates are based on the century of hurricane strikes from 1900 to 1999 (including 1999 storms Dennis and Floyd) and are consistent with probabilities based on observed tropical weather strikes [1]. Even though the annual probability of a hurricane strike *somewhere in the U.S.* is relatively high, the annual probability of a *particular location* experiencing severe tropical weather is quite low.

Table 2 – Hurricane Strike Probabilities for the Case Study Location

Saffir-Simpson Storm Category	NWS HURISK Model [6] Annual Probabilities of Maximum Sustained Winds	Burrus, Dumas, Graham [1] Observed Maximum Sustained Wind Probabilities
Tropical Storm	0.15336	0.17
Cat 1	0.02826	0.04
Cat 2	0.00817	0.00
Cat 3	0.0052	0.01
Cat 4	0.00254	0.00
Cat 5	0.0001	0.00

We now conduct an expected benefit analysis using the HURISK probabilities. We consider a scenario in which conditions are especially conducive to improvement purchases. If purchases are not cost-effective in this hypothetical case, then they are likely not cost-effective in practice. First, we assume that the property and any purchased defensive measures do not depreciate over time. Hence, the owner reaps perpetual benefits from storm surge protection. Second, we assume that the owner does not have the option to purchase flood insurance. (The interaction of structural improvements and insurance purchases is considered in [1].) Third, we consider a location with a relatively high risk of hurricane strikes, Wilmington, N.C.

Given these assumptions, expected storm surge damage in year t, $E(D_t)$, is expressed as:

$$E(D_t) = P4 \cdot D^f{}_4(c^f) + P5 \cdot D^f{}_5(c^f)$$

where P4 and P5 are the probabilities of category 4 and 5 storms. If the structure is completely undefended, the expected annual damages from a "Cat 4" storm are 0.00254 · \$71,726 = \$182.18. Expected annual damages for a Cat 5 are 0.0001 · \$126,382 = \$12.64. Consequently, total annual expected damages are \$194.82. (A home built to code suffers no storm surge damage in tropical storms and hurricane categories 1 though 3.)

Since only one value of c^f is possible for a given structure (the owner cannot defend against a category 5 storm if he purchases only category 4 defense), we first calculate expected damages assuming the property owner defends against a category 4 storm. Using equation (5), if the owner fully defends against a category 4 hurricane, expected damages decrease to 0.00254 · $0 + 0.0001 · $102,065 = $10.21, a savings of $184.61 ($194.82 - $10.21) in *annual* expected damages. Assuming a minimal cost of capital of 6%, the present value of the cat 4 defenses is $3,077 ($184.61/0.06) in perpetuity where the $184.61 in otherwise expected cat 4 damages can be treated as annual "savings"; these savings become a 6% "return" on the $3,076 investment. As this level of "all or nothing" defense costs almost $40,000, the owner does not choose this option. Requiring a higher rate of return further lowers the value of the protection; a 7% "return" requirement yields a present value of the cat 4 protection of only $2,637.

If the owner fully defends against a category 5 hurricane, expected damages fall to $0 annually. The present value of cat 5 defenses, however, is only $3,247 ($194.82/0.06). However, these defenses cost $54,567, and the owner does not choose this option.

Under the most generous assumption of *complete* destruction of the home and its contents in either a category 4 or 5 hurricane which amplifies the value of surge protection, expected annual hurricane storm surge damages are still very low ($604.52 + $23.80 = $628.32). Assuming also that the cheaper cat 4 defenses defend completely against both cat 4 and cat 5 damages, the value of cat 4 defenses is only $10,472 ($628.32/0.06), and the owner opts not to defend. In this most accommodating scenario, the cost of capital must fall to 1.58% for the owner to consider defensive purchases.

VII. Discussion and Conclusions

Hurricane storm surge causes tremendous property damage, and increasing coastal development exacerbates future damage. We investigate the cost-effectiveness of coastal home improvements designed to mitigate this damage. We show how least-cost improvements vary with hurricane intensity, foundation type, and new versus retrofit construction. We develop and parameterize storm surge damage reduction functions for a case study property in Wilmington, NC, the site of several recent hurricane strikes.

We find that the marginal (incremental) benefits of structural improvements, in terms of damage reduction, are increasing in improvement expenditures. Because marginal benefits increase, a property owner engages in interesting "all-or nothing" behavior. In other words, an owner facing a hurricane strike of given intensity purchases either no structural defenses or purchases enough structural defenses to fully protect the property. As hurricane strikes for any particular location are low probability events, the expected benefits of structural improvements *beyond building codes* may not justify the costs, even if flood insurance is unavailable. The owner may be better off investing the money elsewhere and using the proceeds to repair any storm surge damages that arise.

Although representative, our results may not hold strictly for all property types and locations. Regional differences in hurricane probabilities, topography, home design, and building codes imply differences in flood damage-reduction functions. Hence, cost-effective structural defenses likely differ from region to region. Finally, these results may not hold for the extremely risk-averse individual; we are currently investigating the effects of risk aversion on mitigation behavior.

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