Predicting severe winter coastal storm damage

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Abstract

Over the past 40 years residents of, and visitors to, the North Carolina coastal barrier islands have experienced the destructive forces of several ‘named’ extratropical storms. These storms have caused large-scale redistributions of sand and loss of coastal structures and infrastructure. While most of the population living on the islands are familiar with the wintertime storms, the damage and scars of the ‘super northeasters’—such as the Ash Wednesday storm of 7 March 1962, and the Halloween storm of 1989—are slipping away from the public’s memory. In this research we compared the damage zones of the 1962 Ash Wednesday storm, as depicted on aerial photographs taken after the storm, with photos taken of the same areas in 2003. With these high-resolution aerial photos we were able to estimate the extent of new development which has taken place along the Outer Banks of North Carolina since 1962.

Three damage zones were defined that extend across the islands from the ocean landward on the 1962 aerial photos: (1) the zone of almost total destruction on the seaward edge of the islands where the storm waves break; (2) the zone immediately inland where moderate structural damage occurs during severe storms; and (3) the zone of flood damage at the landward margin of the storm surge and overwash. We considered the rate of coastal erosion, the rate of development, and increases in property values as factors which may contribute to changing the financial risk for coastal communities.

In comparing the values of these four factors with the 1962 damage data, we produced a predicted dollar value for storm damage should another storm of the magnitude of the 1962 Ash Wednesday storm occur in the present decade. This model also provides an opportunity to estimate the rate of increase in the potential losses through time as shoreline erosion continues to progressively reduce the buffer between the development and the edge of the sea. Our data suggest that the losses along the North Carolina coast would rank amongst the all-time most costly natural disasters to have occurred in the United States, with up to $1 billion in losses in North Carolina alone.

Keywords: Nor’easters, Northeast storms, Ash Wednesday storm, 1962, Outer Banks, North Carolina, damage model, natural hazard risk

1. Introduction

Severe winter storms are responsible for most of the major landscape changes that occur along the mid-Atlantic coast barrier islands. While these northeasters are normally less intense than hurricanes, they do represent an important force in shaping the coast. Unlike tropical cyclones such as hurricanes, which typically pass over an area in one day or less, nor’easters, as they are commonly called, may persist in a geographic area for several days. Further, with the exception of a few major hurricanes, tropical cyclone damage is typically

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restricted to a relatively small segment of the coastline near the point of landfall, usually within 75 km of the eye (Davis et al. 1993). Winter storms are especially significant from Cape Hatteras northward due to their larger size and longer durations. During severe storms inshore currents capable of transporting great masses of sand and damaging coastal development lead to large-scale landscape changes. High tides and large waves can move water masses, called storm surge, across the coastline and into developed areas.

Along the Atlantic Coast, each year between 20 and 30 wintry extratropical storms generate waves of at least 1.5 m in height that produce beach erosion (Dolan et al. 1988, Davis et al. 1993). Because of their high frequencies and long durations, northeasters actually generate more wave energy than hurricanes each year along the North Carolina coast (Smith et al. 2010). A recent study comparing the impact of hurricanes and northeasters in North Carolina reveals that northeasters produce seven times the total storm wave energy ($H^2$ times duration of waves 1.5 m and higher) of hurricanes (Smith et al. 2010). The Ash Wednesday storm of 1962 exemplifies the destructive force of the most severe winter northeasters (Davis et al. 1993, Mather et al. 1967). The effects of this landmark storm were felt from South Carolina to Maine (Dolan et al. 1988).

Over the past 60 years, seven severe northeast storms have impacted the Outer Banks, two of which fall into the category of ‘super northeasters’. The idea that these storms are associated with significant loss of property and loss of life is not new, but the lack of a ‘super northeaster’ in recent years may be responsible for decreasing public concern over these major winter storms. This research was carried out to estimate the potential property losses that would occur along the Outer Banks of North Carolina as a consequence of a storm of the magnitude of the 1962 Ash Wednesday storm (one of the ‘super northeasters’) if it were to occur again. To make this prediction, we use wind, wave, and property loss information from the 1962 storm combined with land use change information determined by analysis of aerial photographs.

Modeling the financial impacts of environmental disasters continues to receive ample attention in scientific and risk-based literature (e.g., Bouwer et al. 2007). Insurance providers, city planners, first responders, and the general public are amongst the constituencies with a vested interest in quantifying and/or minimizing the burden that severe weather events inflict on human welfare. Although there is uncertainty related to the anticipated future frequency and intensity of major cyclones, researchers estimate that weather-related losses continue to grow annually as the number of people and value of possessions in harm’s way increases (Changnon et al. 2000, Bouwer et al. 2007, Pielke et al. 2008). We contribute one potential method for projecting the financial burden of a single major storm using a combination of historical damage estimates and aerial photographs.

2. The Ash Wednesday storm of 1962

The center of the Ash Wednesday storm remained nearly stationary for several days off of the mid-Atlantic coast, as a strong high pressure system over southeast Canada created a ‘blocking’ pattern inhibiting the storm’s northeast progress (Davis and Dolan 1993). The high storm surge occurred in conjunction with perigean spring tides over four or five successive high tides (Wood 1978). For comparison, in most hurricanes the storm surge may be higher but spans only a few hours (North Carolina Sea Grant 1978). In addition, the combination of the high astronomical tides and continued northerly winds resulted in very high waves. In the early morning hours on 7 March, the lightship Chesapeake recorded sustained winds of 110 km h$^{-1}$, accompanied by waves with heights over 10 m. The ship, stationed 25 km east of Cape Henry, Virginia, was forced to leave its station due to damage from a 15 m wave. Along the coast, tides averaged 1–2 m above normal spring tides, and waves were breaking at heights of 6 m and higher (United States Army Corps of Engineers 1962). Maximum gusts were 135 km h$^{-1}$ at Block Island, Rhode Island, and 128 km h$^{-1}$ off Cape Henry, Virginia (Posey 1962); however, winds alone were not responsible for the damage with the Ash Wednesday storm. While the winds contributed to the formation of high tides and waves, the main damage was caused by the slow movement of the storm and the associated high tides.

The Dolan–Davis scale (table 1) ranks northeast storms into five classes, with the weakest storms in the first two classes comprising 75% of all northeasters impacting the Outer Banks (Dolan and Davis 1992). The Ash Wednesday storm of March 1962 falls into the extreme group, class 5.

Financial losses near the coast from the 1962 storm were major and widespread. In addition, record-breaking snowfall was recorded throughout Virginia and Maryland, including 1 m at several locations in Virginia, up to 240 km inland from the coast. At least 34 deaths were attributed to the storm, and the damage inland and along the coast totaled over $300 million in 1962 dollars, or $2.1 billion in 2010 dollars (Posey 1962, Davis et al. 1993).

| Storm class | Frequency of storms | Significant Wave Ht (m) | Duration (h) | Power ($m^2$ h) |
|-------------|---------------------|------------------------|--------------|-----------------|
|             | Number              | Percentage             | Mean         | Range           |
| 1 Weak      | 670                 | 49.7                   | 2.0          | 8               | 32              |
| 2 Moderate  | 340                 | 25.2                   | 2.5          | 18              | 107             |
| 3 Significant| 298                | 22.1                   | 3.3          | 34              | 353             |
| 4 Severe    | 32                  | 2.4                    | 5.0          | 63              | 1455            |
| 5 Extreme   | 7                   | 0.1                    | 7.0          | 96              | 4548            |

Table 1. The Dolan–Davis classification of Northeast storms. Values determined from 1347 storms between 1942 and 1984.
Table 2. Categorized damages in three locations from the 1962 Ash Wednesday storm, from US Army Corps of Engineers Report RCS ENGCW-0-2, 6 September 1962.

| Location | Damage |
|----------|--------|
| Duck and National Park Service Property | |
| Coquina beach day area | $10,000 |
| Water system | $15,000 |
| Inlet campsite area | $200,000 |
| Inlet marina | $75,000 |
| Destruction to 4 miles of dunes | $50,000 |
| Total | $350,000 |
| Kitty Hawk | |
| Structural damage to buildings | $387,000 |
| Fishing pier structural damage | $20,000 |
| Damage to highway pavement and foundation | $30,000 |
| Sand deposit and water damage | $19,000 |
| Removal of sand deposit on highway | $14,300 |
| Total | $470,300 |
| Nags Head | |
| Structural damage to buildings | $865,500 |
| Fishing piers (2) structural damage | $175,000 |
| Damage to highway pavement and foundation | $40,000 |
| Sand deposit and water damage | $44,000 |
| Removal of sand deposit on highway | $35,700 |
| Total | $1,160,200 |

Damage reports from north of Oregon Inlet were collected by the US Army Corps of Engineers (USACE). Their 1962 report identifies that 16% of all structures in the Outer Banks were either ‘totally destroyed’ or ‘badly damaged’ by the Ash Wednesday storm. In addition to the damage to structures, it was estimated that the shoreline moved inland about 30 m throughout the area and 75% of the protective barrier dunes were destroyed. Table 2 summarizes the damage observed in the region.

3. Coastal development along the Outer Banks since 1962

Despite a long history of major storms and the devastation they cause, development continues along the Outer Banks within high-risk zones along the coast. Between 1990 and 2000, the US Census Bureau reported that 17 of the 20 fastest-growing American counties and 19 of the 20 most densely populated were located along the coast. In total, the 451 coastal counties in the United States that make up 20% of the nation’s land area contain roughly one-half of the nation’s population (United States Census Bureau 2001). North Carolina has been one of the nation’s fastest-growing states within the past decade. Within North Carolina, the fastest-growing county between 1970 and 1995 was Dare County, which comprises the study region (Overton et al. 1999). Dolan and Peatross (1992) note that because of the rapidly increasing coastal populations, less than one-quarter of the residents of the Atlantic and Gulf coast barrier islands have ever experienced the impact of a super northeaster.

We examined the development in three geographic zones along the North Carolina barrier island: Duck, Kitty Hawk, and Nags Head (figure 1). These regions are representative of the rapid development that has occurred within the larger region over a period of 40 years. We offer a model that allows the user to input known damages from the storm of 1962 and output a predicted value for present-decade damage from a storm of similar magnitude. These projections serve as the basis for a prediction on statewide and national damage for storms of similar magnitude.

4. Risk model development

In our analysis, four factors are determined to be important in potential storm damage. The first is the change in property values which in the current era can be considered a positive-change factor, or ‘multipliers’, in the template. We do not include inflation as a risk factor but note that our estimates should be adjusted for inflation to a standardized year when comparing to other major natural disasters or anticipating present-day costs.

Our focus is to understand how changes in development and to the coastline impact total storm damage. Accordingly, we employed aerial photography to estimate the number of structures exposed to varying risks of storm damage in 1962 and 2003. To complete these analyses, we established geographical zones based on locations inland from the waterline. These ‘risk zones’ are identified based on detailed reports of structural damage in the 1962 storm, beach and overwash patterns on the 1962 aerial photographs, and roughly represent the rate of energy dissipation of storm surge across the coast. The zones are defined as: the zone of destruction, the zone of structural damage, and the zone of extensive flooding (figure 2). We believe that this type of classification scheme could be applied to other major extratropical storms, but the specific distances from shorelines estimated here are valid only for a storm equal in magnitude and duration to that of the Ash Wednesday nor’easter.

The zone of destruction is the oceanfront of the three zones. Here, in major storms, structures are essentially
submerged and are constantly impacted by breaking waves and storm surge. The zone of destruction can be thought of as the zone of highest kinetic energy. On average, this zone is estimated to be 60 m wide and is where approximately 50% of the total financial losses occur.

The second zone, the zone of structural damage, is where there is direct wave run-up or structures are affected by surging and flowing water. Structures in this zone are also subject to considerable changes due to the sand movement during storms as the beaches are driven landward. With the March 1962 storm, for example, the deposits of sand driven inland by storm surge averaged 1 m in thickness, and in some locations they were as thick as 2 m (Podušal 1962). This zone averages 150 m in width when severe storms occur and is the location of about 33% of the total financial losses.

The most inland zone, the zone of flooding, is where structures are primarily damaged from standing floodwaters. This zone is typically 300 m in width, and hosts the remaining 17% of damage costs. Although the specific widths of these zones vary based on the magnitude of the storm and local topography, we believe these are reasonable estimates of the distribution of damage caused by a major storm.

High-quality aerial photographs are available for the Outer Banks region for December 1962 and 2003 (University of Virginia 1962, National Oceanic and Atmospheric Administration 2003). The study sites are representative of regions that were both well developed and partially developed in 1962. In general, locations that were undeveloped in 1962 have remained undeveloped. For all three sites, topography, roads, or buildings that have remained in place were used to ensure that the same regions were being consistently analyzed within the photographs. Small sheds, house trailers, and other apparent temporary or small storage facilities were not counted in either set of photographs. Figures 3(a) and (b) show examples of the aerial photos analyzed and table 3 presents structural counts for the three sites in 1962 and 2003. Structures were assigned to one of the three zones based on the estimated zone widths described above. The first zone is considered to begin at the high-water mark.

The first step in our model to project present-decade storm damage is to apportion the damage costs from the 1962 storm. Our estimate of 50%, 33%, and 17% of the damage within each of the three respective zones assumes an equal number of structures fall within each, although this is typically not the case. To appropriately allocate damage costs to each zone, we made a correction for the number of structures based on our damage estimates. We expect nearly three times the damage cost in the zone of destruction as we do in the zone of flooding, and nearly twice the damage cost in the zone of structural damage. In the case of the Nags Head site, there are 100, 181, and 18 structures present in each zone moving inland from the shoreline (and 299 total). We multiply the number of structures in the zone of destruction by 2.94 (50/17) and the number in the zone of structural damage by 1.94 (33/17) to arrive at ‘weighted’ figures of 294, 351, and 18 (663 total). We then divide the total damage ($865,500) into each zone proportional to the damage-weighted count (see table 4). The final calculation is the estimated damage per structure, determined by dividing the per-zone damage by the actual (not corrected) number of structures. Our damage per structure estimate is not (and need not be) representative of the actual damage per structure because we are comparing identical stretches of the coast between two points in time. The damage per structure estimates from one study region to another should not be compared.

To project 2003-equivalent storm damage, we multiply the damage per structure figures (1962 dollars) calculated above by the actual number of structures observed in the 2003 aerial photos. Changes to the shoreline configuration are implicitly included in this calculation because the damage zones are drawn independently for each of the two sets of photographs.

5. Results

The factors we use to predict 2003-equivalent storm damage in the Outer Banks are property value, development, and beach erosion. The median home price for the entire state of North Carolina increased from $39,400 to $108,300 between 1960 and 2000 (in $2000), the equivalent of a 2.5% average annual increase (United States Census Bureau 2004). The median home price in Dare County in 2000 was $137,200 (United States Census Bureau 2004), and the mean selling price for Outer Banks homes across North Carolina in 2000 was $249,085 ($2000) (North Carolina Association of Realtors 2001). We were unable to obtain information specific to Dare County home prices in the 1960s, but our personal experience suggests that over the last 50 years the value of coastal properties in Dare County has appreciated at an average annual 7% nominal rate (Dolan owned property in Dare County for over 20 years). If we compromise between the statewide census estimate and our local estimate, property values in our study sites have increased by roughly a factor of 7 (5% average increase over 40 years) between 1962 and 2003.

We recognize that the rate of increase varies by property and consider our value conservative. The geographic variation in development is different for each of the three study transects. In the case of Nags Head, most development has occurred inland from the immediate shoreline—the zone of flooding contained 300 structures in 2003 compared to just 18 in 1962. Despite a high rate of development most new buildings have been constructed well inland from the shoreline. As such, the increased risk is lower than in Kitty Hawk, where construction has occurred more evenly. On the other hand, the Duck transect presents an atypical case for the Outer Banks—a region that was almost wholly undeveloped in 1963 that today

| Table 3. Structure counts from three sites in the North Carolina Outer Banks in 1962 and 2003, along with associated ‘Development Factor’. |
|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Nags Head         | Nags Head       | Kitty Hawk      | Kitty Hawk      | Duck            | Duck            |
| 1962              | 2003            | 1962            | 2003            | 1962            | 2003            |
| Zone of destruction | 100            | 101            | 81              | 182            | 5              | 90              |
| Zone of structural damage | 181          | 242            | 255            | 384            | 3              | 246             |
| Zone of flooding | 18              | 300            | 141            | 896            | 0              | 528             |

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Figure 2. Estimated damage zones during a major extratropical storm in the Outer Banks of North Carolina. The damage zones here are illustrated along a section of the Outer Banks coastline near Duck, NC.

Figure 3. Aerial photographs near the Wright Memorial near Kitty Hawk, NC for 1962 (left) and 2003 (right).

hosts a populated town. In our Duck transect there were only eight total structures in 1962; in 2003 there were 864. The relative change in damage costs in this region is high but not representative of most of the coastline along the Outer Banks and much of the Atlantic seaboard. To project a present-decade estimate of damage from a storm similar in magnitude to that of the Ash Wednesday storm, we multiply the damage projections (table 5) by the increases related to property value change (table 6).

The damage from the 1962 storm in the areas of Duck, Kitty Hawk, and Nags Head alone totaled nearly $2 million (in 1962 dollars). Our damage estimates for a present-decade Ash Wednesday storm are $9737 000 for Nags Head (in $1963) and $6748 000 for Kitty Hawk. It is more difficult to estimate the damage for Duck, but as our transect includes an intermediate number of structures between those for Nags Head and Kitty Hawk, it is reasonable to assume the damage there may also fall in the $6–10 million range ($1963). Collectively, if this type of storm were to hit today, the damage could surpass $22,000,000 in $1963 for these three sites alone (table 6). Total damage across the state of North Carolina for the Ash Wednesday storm was roughly $12 million—these three sites accounted for about 16.5% of the damage then (United States Army Corps of Engineers 1962). Using the same ratio, if the
storm were to hit today, North Carolina could suffer over $130 million in losses in $1963. From this estimate we are able to glean that because of increased coastal development, changes to the coastline, and increases to property values, the storm’s financial impact could be ten times greater than it was in 1962. Applying the same technique to estimate a national loss gives the coastal storm’s expected damage in the zone of flooding. The damage per structure is determined by dividing the estimated damage in each zone by the actual number of structures within the zone.

### Table 4. Weighted number of structures in each damage zone based on estimates of expected damage. The weighted counts are determined by multiplying the observed number of structures in each zone by the ratio of the expected damage in that zone to the expected ratio of regional damage. The damage per structure is determined by dividing the estimated damage in each zone by the actual number of structures within the zone.

|                       | Expected damage | Nags Head 1962 | Weighted counts | Damage per structure | Kitty Hawk 1962 | Weighted counts | Damage per structure |
|-----------------------|-----------------|----------------|-----------------|----------------------|-----------------|-----------------|----------------------|
| Total damage          | $865 500        | 100            | 294             | $387 000             | $1302           | 238             | $859                 |
| Zone of destruction   | 50%             | 50%            |                 |                      |                 |                 |                      |
| Zone of structural damage | 33%         | 181            | 351             | $253 200             | 95              | 495             | $859                 |
| Zone of flooding      | 17%             | 18             |                 | $1304 000            | 14              | 141             | $443                 |
| Total damage projection ($1963) | $9737 000 | $6748 000     | $387 000        | $1302 000            | $237 000        | $330 000         | $397 000             |

### Table 5. Projections of damage from a storm equal in magnitude to that of the 1962 Ash Wednesday storm based on the number of structures present in 2003 and the estimated damage per structure in 1962 from table 4 (in 1962 dollars).

|                       | Nags Head 1962 | Nags Head 2003 number of structures | Kitty Hawk 1962 | Kitty Hawk 2003 number of structures | Kitty Hawk 2003 damage cost ($1962) |
|-----------------------|----------------|-----------------------------------|-----------------|-------------------------------------|-----------------------------------|
| Zone of destruction   | $387 000       | 101                                | $1302           | 182                                 | $237 000                          |
| Zone of structural damage | $253 200 | 242                                | $859            | 384                                 | $330 000                          |
| Zone of flooding      | $1304 000      | 300                                | $443            | 896                                 | $397 000                          |
| Total damage          | $964 000       |                                    |                 |                                     |                                   |

### Table 6. Adjustment of the damage projections from table 5 to 2003 dollars based on increasing property values. The $1963 projection does not include any inflationary adjustment.

|                       | Nags Head 1962 | Nags Head 2003 number of structures | Kitty Hawk 1962 | Kitty Hawk 2003 number of structures | Kitty Hawk 2003 damage cost ($1962) |
|-----------------------|----------------|-----------------------------------|-----------------|-------------------------------------|-----------------------------------|
| Total damage          | $1391 000      | 7                                 | $964 000        | 7                                   | $6748 000                         |

### 6. Discussion

The effects of the coastline’s changing resistance to storm damages and related protection of structures, as well as changes in construction practices that have improved the ability of structures to withstand high winds, waves, and storm surge are outside the scope of this search. Human development along the shoreline decreases this natural protection from storm-driven forces. It is particularly difficult to create a quantitative value that describes how the buffer effects have changed. Further, we recognize that improvements to construction practices represent a significant factor unaddressed by our research. More stringent building codes, as well as improved materials used in construction, make modern structures especially resistant to the impacts of waves, wind, and floodwaters. However, Fronstin and Holtmann (1994) found the opposite to be true for structures in Florida damaged by Hurricane Andrew: a higher percentage of newer homes were destroyed in the storm because of weakened building codes. We also acknowledge that our method simply counts the number of structures in a given area and not the specific types of buildings that exist, which introduces some error into our estimate.

Many have debated the recurrence of a storm of the same magnitude as the Ash Wednesday nor’easter. Cooperman and Rosendal (1963), for example, recognize the slow movement of the Ash Wednesday storm of 1962 and the associated tidal damage occurring over several tidal cycles as one of the major factors contributing to the overall damage and that the associated synoptic conditions should be reflected in the five day mean pressure pattern for the time of the storm’s impact. They performed a statistical analysis on the pressure pattern alone, disregarding the effect of the astronomical tides to determine how unusual the synoptic conditions were. Their study showed that the mean pressure values of March 1962 were not outstanding. The return periods for the strength of the associated cyclone and anticyclone for the storm were five and two years, respectively. If the return periods for the easterly flow between 35° and 45°N are considered as an index for storm intensity, the storm’s return interval becomes closer to 11 years. If this flow is assumed independent of the lunar cycle, the return period for similar flow occurring during a maximum spring tide, as was the case during the Ash Wednesday storm, becomes 60 years. Therefore, their work suggests that it is not unlikely that a similar event will occur before major changes in land use in the Outer Banks take place.
7. Conclusion

Our model estimates that the financial losses of a present-decade northeast storm of the magnitude of the Ash Wednesday storm of March 1962. We rank the storm amongst the most costly in United States history. This study only deals with direct losses; however, the impacts of a major storm can be noticed for years in a community’s economy. Damage from natural disasters frequently results in interruption to business and tourism. Quantitative estimates of this value would have a high range of potential error, but would add to the cost estimated in this study. Future work is suggested in determining quantitative values for the factors not utilized in the template: this work is offered only as a starting point.

Understanding the potential consequences of a major storm impacting some of the nation’s most developed regions is important as changes come about in land use strategy, policymaking, and insurance programs. More sensible strategies in coastal development must be considered if the tragedies of a storm like that of March 1962 are not to be repeated.

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