CHAPTER 212

# PREDICTING DAMAGE BENEFITS OF SHORE PROTECTION PROJECTS

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## ABSTRACT

A numerical simulation method is described to estimate damage and associated benefits to oceanfront (and "backrow") properties without-, with- and adjacent to shore protection project areas. Damage to structures, land, and structure contents is described -- as is the effect of shoreline armoring. Input data include property attributes and estimates of beach recession for various intensity storms. Projects are described by their geometry, life expectancy, construction intervals, and effect upon the chronic and storm-induced recession. Projects can include nourishment, armoring, or other types which have a quantifiable effect upon chronic and storm-induced recession. Damage is computed based upon (1) the encroachment of the eroded bluffline to the property by chronic (historical) erosion stress and by storms, and (2) functions which depend upon structure type or land use. Spatial and temporal resolution is adaptable to the user's needs.


## 1. INTRODUCTION

Shore protection projects such as beach nourishment, dune enhancement, and shoreline armoring decrease the potential damage to upland properties associated with chronic annual erosion and episodic storm events. These effects are central to the benefit/cost and cost-sharing analyses necessary for most shore protection projects. While a basic approach to predicting shorefront damage generally exists, actual methodologies are not standardized and vary greatly in their level of sophistication.

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This paper presents a rational, automated technique to predict shorefront damage due to combined chronic and episodic storm-related beach erosion. Damage due to flooding and wind are excluded. The technique utilizes input data which are fairly readily obtainable. Damage to any particular property is predicted as a function of the property's structural, siting, and beach-profile characteristics. Individual rows of property (shorefront, second row, third row, etc.) can be separately evaluated. Both existing and simulated post-project conditions can be evaluated in a year-by-year, property-by-property approach with various levels of temporal and spatial resolution, as desired. The effects of a project both inside and outside the project area can be investigated. The results can be used directly in a benefit/ cost analysis or can be used to develop a project's cost-sharing formulae. Additionally, the technique complies with current U.S. Federal guidelines regarding prediction of storm damage benefits of coastal works (U.S. Army, 1989).

## 2.0 OVERVIEW OF METHOD

The technique requires that shorefront properties be grouped into contiguous, self-similar parcels. Data which decribe physical and economic attributes of the property within each parcel are tabulated (Section 3.2). The recession due to various return-level storm events is then predicted for each property parcel through a dune-erosion (or similar) model (Section 3.3).

Damages to property are calculated by "tracking" changes of a reference location on the beach. This, in turn, allows one to track changes in the setback distance between the property and the reference location. This reference location is typically the vegetation line, dune crest or bluff escarpment -- and is hereafter referred to as the "bluffline". Changes in the bluffline location may be the result of (i) chronic (historical) erosion stress, (ii) storm induced erosion, and/or (iii) a shore protection project.

The method by which property damage is computed is identical for with- and without-project conditions. The effect of a shore protection project is accounted for by changes in bluffline location and storm recession estimates. Damage benefits of a shore protection project are simply the difference between the damages computed for with- and without-project conditions.

The actual damage prediction algorithm is in the form of a numerical simulation. <u>Input</u> to the simulation includes two data files: The "property" data base includes economic values and various physical characteristics of each of the property parcels along the study area. The "erosion" data base includes estimates of dune recession expected for various-intensity storm events for each of the property parcels. Output from the simulation includes, for each time step, the cumulative damage to structures and the loss in land value at each of the property parcels.

## 3.0 PREPARING INPUT DATA

### 3.1 Parcel Division

The shorefront properties are first grouped into contiguous parcels self-similar in (1) beach profile characteristics, (2) property depth, (3) structural set-back, (4) structure size and construction-type, and (5) historical shoreline erosion rate. If cost-sharing estimates are of interest, then the use or function of the properties within each parcel should also be similar. That is, publicly-owned properties should be isolated from privately-owned properties; commercial properties should be isolated from residential properties, etc.

The shore-parallel length of each parcel is not particularly important. It is only important that the properties within each parcel are self-similar, and that the parcels are not so long that they obscure potential project boundaries.

It is convenient to establish an artificial baseline along the shorefront's bluffline by which the endpoints of each parcel can be referenced. A baseline with 1000-ft or 200-m station intervals drawn upon aerial photographs or plat maps is usually appropriate.

### 3.2 Property Data Base (Input)

For each property parcel, the following items are identified (see Figure 1):

(1) location along a shore-parallel baseline, $Y_1$ & $Y_2$;
(2) structure value, $V_S$;
(3) land value, $V_L$;
(4) average set-back distance of the structures from the initial (year-zero) bluffline, S;
(5) average footprint (depth) of the structures, F;
(6) lot depth, L;
(7) structure type (piles, slab-on-grade, etc), $S_t$
(8) historical bluff or dune erosion rate, dx/dt; and
(9) an index number identifying the appropriate storm recession data which apply to the parcel (see Section 3.3).

These data (for each parcel) are entered to a data file. Items 1 through 7 are developed through aerial photography, ground truthing, and appraisal or tax records. Item 8 is developed through historical shoreline analysis. Item 9 is described below.

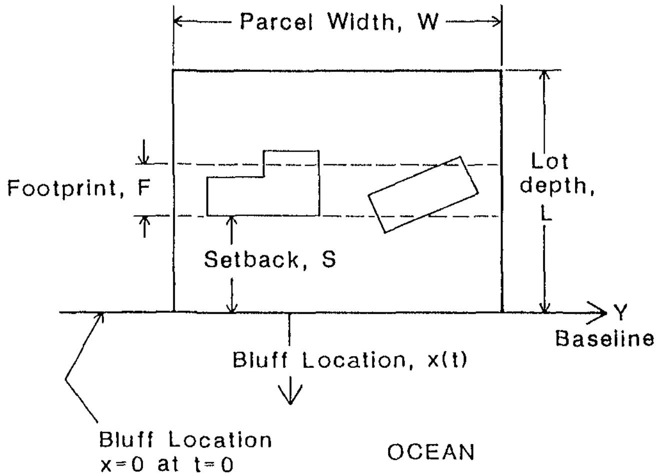


Figure 1: Attributes of an oceanfront property parcel.

### 3.3 Storm Recession Data Base (Input)

For several representative beach profiles along the study area, the recession of the existing (year-zero) bluffline is predicted for K storms of various return-period intensity using a dune erosion model. This is done for both existing (no-project) conditions and simulated post-project conditions. In this way, a pair of storm recession estimates is computed for each representative beach profile which includes

* without-project conditions, $R_{ok}$, and
* with-project conditions, $R_{pk}$.

(See Figure 2). The subscript k refers to various return period storm intensities; e.g., k=1 is a 5-yr event, k=2 is a 10-yr event, etc. Generally, K=5 to 10.

An identifying index number is assigned to each pair of storm recession estimates. One of these index numbers is then assigned to each property parcel (item 9, above) to describe the storm recession for that parcel. For quasi-uniform alongshore conditions, a single profile (or single pair of storm recession estimates) will usually characterize several adjacent parcels.

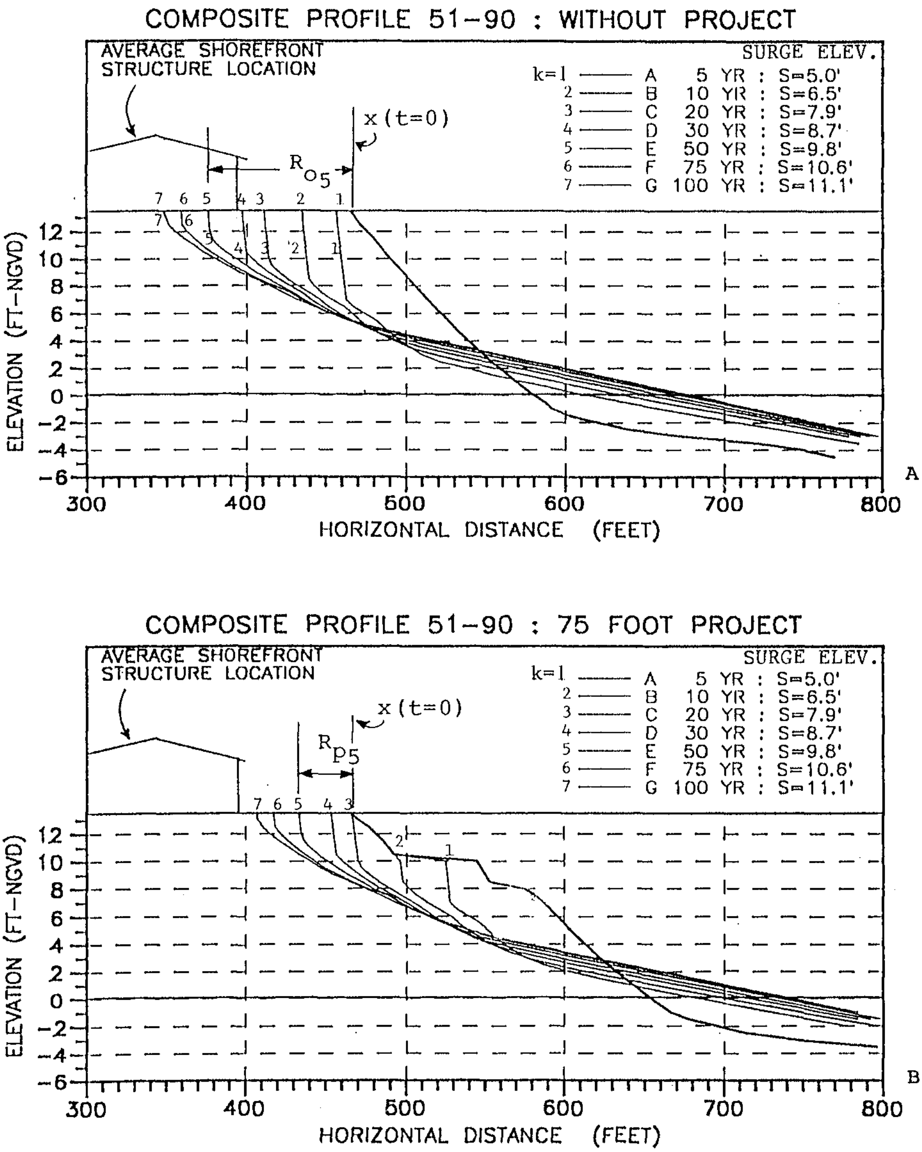


Figure 2: Storm recession for (a) without- and (b) with-project conditions. The recession R for storm k=5 is indicated for both.

## 4.0 COMPUTING EROSION DAMAGE AND BENEFITS

### 4.1 Tracking Non-Armored Bluffline Location

**Chronic (Historical) Erosion Stress** - For each time step $\Delta t$ (usually one year), the present position of the bluffline x(t) for each parcel is updated based upon historical trends or current project conditions. In the absence of an active beach nourishment project (or shoreline armor), the bluffline position x at time t is

$$x(t) = x(t_r) + (t-t_r-z)\frac{dx}{dt} \qquad \text{for } (t-t_r) > z \qquad (1)$$

where $x(t_r)$ is the bluffline location at the time of the most recent nourishment $t_r$, z is the project life, and $(t-t_r) > z$. If there have been no nourishments, then $t_r=t_o$ (where $t_o$ is the initial time t=0), and z=0.

In the presence of an active beach nourishment project, the bluffline position is computed as a function of the project's life z and initial equilibrium berm width W:

$$x(t) = x(t_r) + (1 - (t-t_r)/z)\ W \qquad \text{for } (t-t_r) \leq z \qquad (2)$$

where $t_r$ is the time of the last nourishment, and where $(t-t_r) \leq z$. If $(t-t_r) > z$, then the project is not "active" and Equation 1 applies. (If the beach is historically accretive such that dx/dt > 0, then the value $(dx/dt)\Delta t$ can be added to the right hand side of Eq. 2. However, it is unusual that a shore protection project would be built upon an historically accretive beach.)

For parcels downdrift or adjacent to an active nourishment project, historically erosive shoreline change rates (dx/dt) are set to zero to conservatively simulate the effects of beach fill "feeding". Alternately, an alongshore diffusion model could be used to modify the dx/dt values adjacent to a project (Dean, 1988; Phlegar and Dean, 1989).

**Storm Erosion** - In the absence of an active beach nourishment project (or shoreline armor), the bluffline location resulting from a given storm is the superposition of the current [no-storm] bluffline location, x(t), and the storm's recession estimate $R_{ok}$:

$$x_k(t) = x(t) + R_{ok} \qquad \text{for } (t-t_r) > z \qquad (3)$$

where $R_{ok}$ is the computed "no-project" recession for storm k. If $(t-t_r) \leq z$, then a project is "active" and Equation 3 is replaced by Equation 4, below.

In the presence of an "active" beach nourishment project, the bluffline location resulting from a given storm is the superposition of the [no-storm] bluffline location prior to the nourishment, $x(t_r)$, and the storm recession R -- where R is the given storm's recession estimate tempered by the project's status. During the first year of an "active" project, R is simply the storm recession computed for full-project conditions; $R=R_{pk}$. As the project approaches the end of its life, R approaches the storm recession computed for no-project conditions; $R=R_{ok}$. Between these limits, the storm recession is computed linearly. That is,

$$x_k(t) = x(t_r) + (1-(t-t_r))R_{pk} + (t-t_r)R_{ok} \qquad \text{for } (t-t_r) \leq z \tag{4}$$

Note that Eqs. 3 and 4 implicity assume that the recession for various storm events is independent of the current bluffline location. For real beaches, this is not true unless the beach and dune profile remains geometrically similar as the shoreline chronically retreats or advances each year. However, this assumption eliminates the time-consuming task of re-computing the storm erosion for each chronic change of the bluffline location.

### 4.2 Tracking Armored Bluffline Location

**Chronic** Erosion **Stress** - For parcels which are predominantly armored, the chronic erosion rate of the bluffline, dx/dt, is equal to zero in Eq. 1 -- until the armor is estimated to fail due to chronic erosion stress.

The year at which existing armor might fail can be estimated in several ways; e.g.,

1.) The chronic erosion rate can be transformed to a volumetric rate -- and the impact of this cumulative volumetric loss to the armor's toe stability can be projected to a year of catastrophic failure.

2.) The return-period of the storm surge which will result in a wave height significantly exceeding the armor's design condition can be computed. This return-period can then be conservatively assigned as the armor's ultimate life. (This simplistically assumes that the catastrophic storm which will destroy the armor is certain to occur at least within the storm's return period interval.)

The results of both techniques should be computed and compared in order to guide selection of a reasonable life-span of the armor.

Subsequent to armor failure, the bluffline location is assumed to rapidly retreat to the location of the bluffline at the adjacent parcels. A simple geometric simulation of this is to set the armored parcel's post-failure erosion rate to:

$$dx/dt = \frac{1}{2}\left(x(t-\Delta t) - x(t)\right) \tag{5}$$

where $x(t-\Delta t)$ is the bluffline location at the armored parcel's previous time step, and $x(t)$ is the average current location of the bluffline at the immediately adjacent parcels. This implies that the "bulge" in the shoreline left by the failed armor will only be $1/2^n$ of its initial size at n-years after the failure. That is, the shoreline at the previously armored parcel will be within 12.5% of the neighboring shorelines after 3 years, and within 3% after 5 years, etc.

Storm Erosion - At armored properties, storm recession is generally zero for storms less severe than that storm which is estimated to cause armor failure. The severity of this catastrophic storm can be estimated by: (1) examining the extent of toe scour predicted at the armor's toe for various storms, or (2) back-calculating the storm surge (and its frequency) which would produce waves significantly beyond the armor's design condition. Both techniques require one to consider both no-project and with-project conditions. For storms more severe than that which is estimated to cause armor failure, the recession can be computed by simply ignoring the armor -- or preferably, by failing the armor during the storm event.

## 4.3 Damage Computation for Structures

The damage to shorefront structures due to both chronic (historical) erosion stress and storm-induced erosion is a function of the bluffline's location relative to the structures' set-back S and the structures' footprint F. That is,

$$\begin{aligned} d_s(t) &= f\{\,-(S+x(t))/F\,\} \cdot V_s \\ &= f\{u\} \cdot V_s \end{aligned} \tag{6}$$

where $d_s(t)$ is the dollar damage to structures at year t due to chronic erosion stress, and where $x(t)$ is given by Eq. 1 or 2.

Likewise,

$$\begin{aligned} \hat{d}_{sk}(t) &= f\{\,-(S+x_k(t))/F\,\} \cdot V_s \\ &= f\{\hat{u}\} \cdot V_s \end{aligned} \tag{7}$$

where $\hat{d}_{sk}(t)$ is the the dollar damage to structures in year t due to storm k, and where $x_k(t)$ is given by Eq. 3 or 4.

The nature of the function f{u} or f{$\hat{u}$} in Eqs. 6 and 7 is determined by the structure type. The following are suggested examples. In each, u and $\hat{u}$ are interchangeable.

For slab-on-grade foundations:

$$f\{u\} = \begin{cases} 0 & \text{for } u < 0 \\ 2\,u + 0.1 & \text{for } 0.45 \geq u \geq 0 \\ 1.0 & \text{for } u > 0.6 \end{cases} \tag{8}$$

such that the structure is 100% damaged if the bluffline or storm recession extends through 45% of the structure's footprint. Some damage (10%) occurs when the bluffline or storm recession reaches the seaward face of the structure.

For some spread-footer or non-engineered pile foundations:

$$f\{u\} = \begin{cases} 0 & \text{for } u < 0 \\ u & \text{for } 1.0 \geq u \geq 0 \\ 1.0 & \text{for } u > 1.0 \end{cases} \tag{9}$$

in which case the structure is 100% damage when the bluffline or storm recession extends to the landward edge of the footprint.

For engineered structures on piles or substantial spread-footers:

$$f\{u\} = \begin{cases} 0 & \text{for } u < 0 \\ 2/3\ u & \text{for } 1.5 \geq u \geq 0 \\ 1.0 & \text{for } u > 1.0 \end{cases} \tag{10}$$

such that 100% damage occurs only when the bluffline or storm recession extends 50% of the structure's footprint beyond its landward edge.

While the damage caused by <u>chronic</u> erosion in a single year is simply that of Eq. 6, the damage expected in a single year due to <u>storms</u> is determined by the storms' probabilities of occurrence. That is, the probabilistic -- or expected -- storm damage in each year is the weighted sum of the damage estimated for each of the K storm events considered. This is estimated by:

$$E[\hat{d}_s] = \hat{d}_s = p_1 \frac{\hat{d}_{s1}}{2} + \sum_{k=2}^{K} (p_{k-1} - p_k) \frac{\hat{d}_{sk-1} + \hat{d}_{sk}}{2} \tag{11}$$

Maximum Damage Limit - Maximum limits should be placed on structure damage. For example, it is convenient to assume that a structure will be demolished or relocated (and removed from analysis) if its cumulative damage exceeds some multiplier of its original value (say, 1.5) -- or if the probabilistic damage in a single year exceeds, say, 50%.

Additionally, structures can be demolished or relocated when the bluffline location x(t) reaches a critical distance from the structure's seaward edge. Criteria vary locally. For example, in North Carolina (USA), the rule is 10 ft (3 m) plus 5.0 times the average annual erosion rate. The cost of relocation or demolition can be included in the analysis at the appropriate year.

## 4.3 Computing Damage to Structure Contents (Furnishings)

If damages to contents are to be considered, it is imperative to identify only those damages associated with erosion or with the flooding which may be prevented by the project under consideration (if any). Contents damage due to chronic (historical) erosion is assumed to be zero (because it is assumed that the owner will have plenty of time to remove the contents before chronic erosion causes damage). However, storm erosion may cause damage to contents due to its unexpected nature.

For storms which are not anticipated to cause flooding beyond that prevented by the shore protection project (if any), contents damage is conservatively assumed to occur at half the magnitude of the structure's damage function. (For example, if 40% of the structure value is lost, 20% of the contents value is lost. The other 80% is assumed to be salvageable.) For storms which cause flooding beyond that prevented by the project, no contents damage is calculated. This conservatively assumes that all contents damage is due to flooding and none is due to erosion.

The value of a structure's contents is assumed to be a fraction, c, of the structure's value, $V_s$. The fraction c depends upon the structure's use. From insurance underwriters,

| | |
|---|---|
| Single- & Multi-Family Residences: | c = 0.55 |
| Restaurants: | c = 0.35 |
| Hotels & Motels: | c = 0.25 |

Concisely, the damage to contents for storm k in year t is:

$$d_{ck}(t) = f\{\hat{u}\} \cdot c \cdot V_s \quad \text{for storms w/o flooding} \qquad (12)$$
$$= 0 \quad \text{for storms w/ flooding}$$

where f{ } is from Eq. (7), or as from Eqs. (8), (9), or (10). The probabilistic contents damage in each year is found as through Eq. 11, above.

### 4.4 Computing Damage to Land

Loss of coastal land value may be due to (1) chronic erosion and/or (2) acute storm impacts. To ensure conservative valuation (and to avoid potential "double-counting") the author accounts only for the former. This implicitly assumes that land lost to a storm recovers 100% (minus any chronic year-to-year losses).

Generally, loss of land value at time t is expressed as:

$$d_L(t) = g\{ -x(t)/L \} \cdot V_L \tag{13}$$

where g is a function of the eroded bluffline location x(t) relative to the lot depth L, and $V_L$ is the original (non-eroded) land value. The function g{} can vary; i.e.,

1.) Land value is lost linearly with erosion:

$$g\{ -x(t)/L \} = \begin{cases} -x(t)/L & \text{for } -x(t)/L \leq 1 \\ 1.0 & \text{for } -x(t)/L > 1 \end{cases} \tag{14}$$

This is identical to assuming that land is valued uniformly.

2.) Land value is lost in proportion to erosion, but the lot is completely de-valued when the erosion reaches a certain fraction, a, of the total lot depth L:

$$g\{ -x(t)/L \} = \begin{cases} -1/a \; x(t)/L & \text{for } -x(t)/L \leq a \\ 1.0 & \text{for } -x(t)/L > a \end{cases} \tag{15}$$

where, for example, a = 2/3.

3.) Land value is lost in proportion to erosion, but the lot is completely de-valued when some "minimum" lot depth $L_{min}$ is left:

$$g\{ -x(t)/L \} = \begin{cases} x(t)/(L_{min} - L) & \text{for } -x(t) \leq L-L_{min} \\ 1.0 & \text{for } -x(t) > L-L_{min} \end{cases} \tag{16}$$

### 4.5 Cumulative and Present-Worth Damage & Benefits

The predicted damage which occurs over the time step t at time t is the sum of (1) the probabilistic storm damage d at time t (Eq. 11), and (2) the increase in damage due to chronic erosion between time t and the previous time step, i.e., from $d(t-\Delta t)$ to $d(t)$.

For example, structure damage over the time step $\Delta t$ at time t is

$$D_S(t) = \hat{d}_S + [\ d_S(t) - d_S(t-\Delta t)\ ] \tag{17}$$

The present worth (P.W.) of this damage is

$$DPW_S(t) = D_S(t) * (1+i)^{-t} \tag{18}$$

The cumulative structure damage at year t is simply

$$\int_0^t D_S(t)\ dt$$

and the P.W. equivalent is simply $\int_0^t DPW_S(t)\ dt$.

Project benefits are simply the difference in damage computed for without- and with-project conditions. This can be calculated on, for example, a year-by-year basis (Eqns. 17 & 18), or on a cumulative basis.

## 4.0 DISCUSSION

The simulation technique and algorithms described above feature useful flexibility, some features of which are highlighted below.

Sensitivity of Damage Functions - The damage functions for structures, f{}, and land, g{}, are defined functions -- and can be easily modified for sensitivity tests without altering the rest of the simulation code. While damage functions are suggested herein for various structures and land conditions, others can be easily created and tested as appropriate to the study area.

Project Simulation - Virtually any traditional shore protection project can be analyzed by the technique. The parameters which describe the project's effects appear in three controlled groups: (1) project characteristics (i.e., boundaries, life, width (if applicable), construction interval/timing, and storm intensity up to which flooding is prevented (if any); (2) chronic erosion rates (dx/dt), and (3) storm recession data.

"Backrow" Properties - Properties two, three, or more "rows" from the oceanfront can be explored by creating additional property data bases. For these, the structural set-back distance is the total distance from the structure's seaward face to the bluffline, as usual. Land loss is computed by accounting for the "margin" of land, M, between the subject property and the bluffline. Equation 13 then becomes:

$$d_L(t) = g\{\ -(M + x(t))\ /\ L\ \} \cdot V_L \tag{19}$$

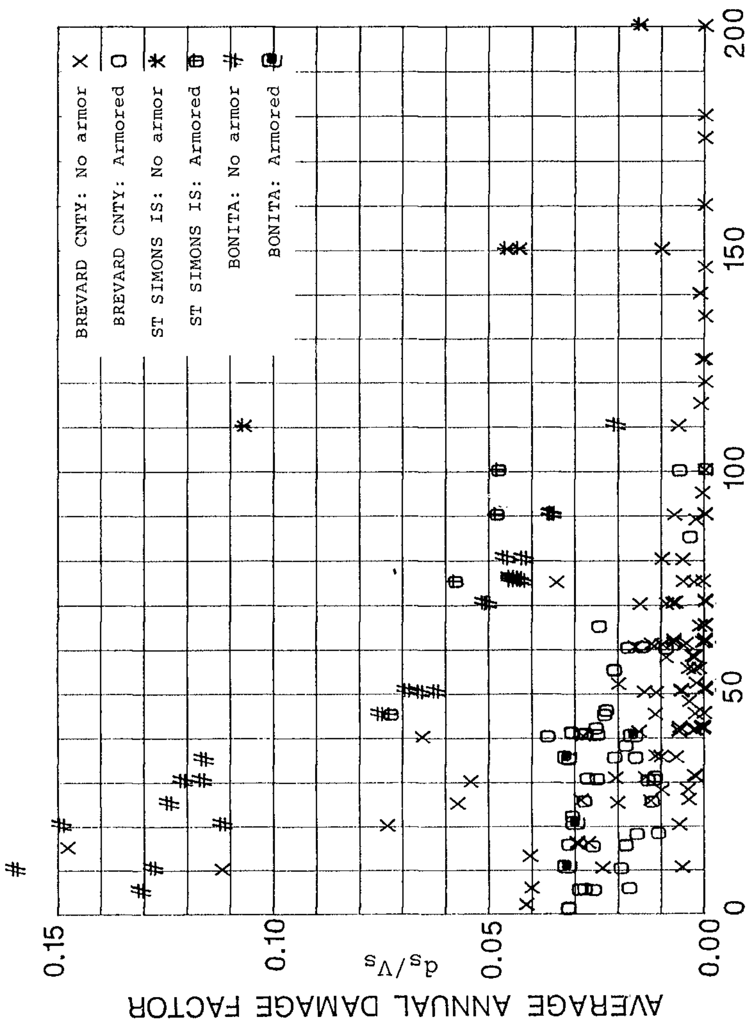


Figure 3: Average expected storm damage to structures (normalized by structure value).

such that loss of land value does not occur until the recession extends through the margin and into the "backrow" lot.

**Simplification of Damage Functions** - Damage to a property is a function of many parameters: e.g., set-back, width, storm frequencies, beach profile, storms, chronic erosion rates, structure type, local armoring, etc. Because each is of similar importance, attempts to express an average damage multiplier as a function of only one or two of these parameters is not advised. As an example, Figure 3 depicts the annual probabilistic (expected) storm damage vs. the local set-back distance for (i) 179 property parcels along a 40-mile segment of Brevard County, Florida, (ii) 21 parcels along a 3-mile segment of Bonita Beach, Florida, and (iii) seven parcels along a 2-mile segment of St. Simons Island, Georgia. While a general envelope is suggested, a simple relationship is not discernable. Inclusion of one or two additional parameters does not significantly improve the correlation (Bodge, in review).

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