BEACH NOURISHMENT: BENEFITS, THEORY AND CASE EXAMPLES

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Abstract

Beaches provide a wide range of societal benefits including storm protection, recreation, and habitat for a number of species. However, many beaches are under natural and/or human induced erosional pressures. The engineer is left with few choices to address this erosional pressure: (1) Correct the erosional cause which is usually practical only if the cause is human related, (2) Retreat from the shoreline, (3) Armor the shoreline, and (4) Beach nourishment which comprises the placement of large quantities of good quality sand in the nearshore system. In many cases, beach nourishment is the only practical environmentally friendly approach of those identified. Emphasis is directed to the benefits of beach nourishment and methodology which identifies the critical design factors. The application of a simple numerical model to predict the performance of two case examples is illustrated.

1. Beaches, Beach Erosion and Available Engineering Options

Beaches provide many benefits to society and the natural system. These benefits include storm protection to upland structures, recreational opportunities especially in urban settings and habitat for a number of species. Many of the World's shorelines are eroding at varying rates due to both natural and/or anthropogenic causes. Due to the attractiveness of shorelines for commercial and residential sites, erosion is of increasing concern and methods are often sought to address this issue.

There are surprisingly few options to deal with an eroding shoreline: (1) Correct the cause of the erosion, (2) Retreat from the shoreline, (3) Employ structures, and (4) Beach nourishment. The ideal option would be to correct the cause of erosion; however, this is usually only possible in limited cases in which the cause is due to anthropogenic activities, such as harbor development that interrupts the net longshore sediment transport, trapping of sand in constructed upland reservoirs, sand mining, inducement of ground subsidence through withdrawal of hydrocarbons or other ground fluids, etc. In the case of interruption of longshore sediment transport, correcting the cause requires reinstatement of the net longshore sediment transport. Retreat from the shoreline is only practical on shorelines that are relatively undeveloped and this option is increasingly less attractive with the trend of coastal development. Examples of the structural option include construction of groins and/or coastal armoring such as seawalls or revetments, each of which has some adverse effects. Groins trap sand from the littoral system, thus stabilizing the beach; however, in

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the process, the erosional stress is transferred to the downdrift beaches. Properly constructed coastal armoring will protect the upland; however, when placed on a receding shoreline, the beach will narrow and gradually disappear. Thus, of the four options available, in many cases beach nourishment is the only option that is "environmentally friendly". If the nourishment is constructed of sediments similar to the native sediments, any disruption to the ecology of the beach system will be temporary and the benefits of the beach will replicate those of a natural but wider beach. The following section focuses on the broad benefits of a wide beach.

1.1 Benefits of Beach Nourishment

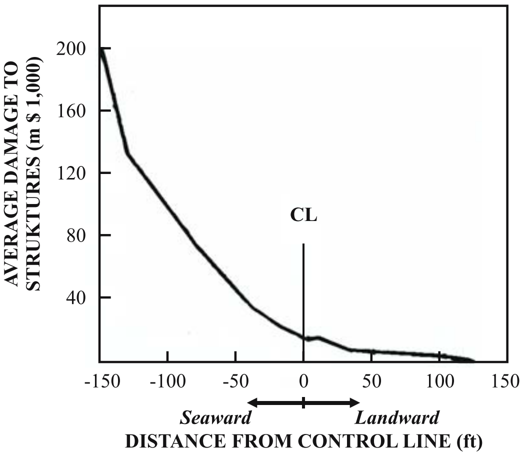
The primary benefits of beach nourishment include: Storm damage reduction, recreation, and habitat, each of which is discussed below.

1.2 Storm Damage Reduction

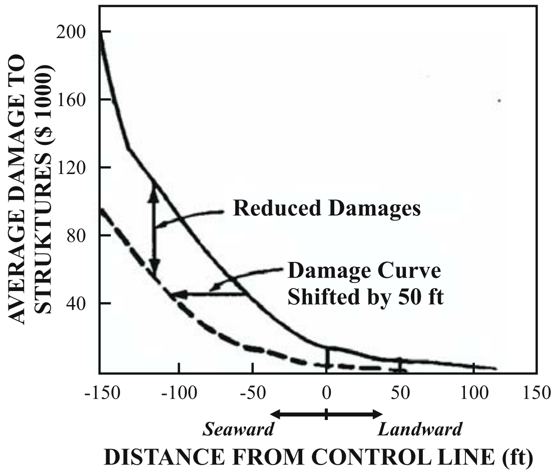
A wide beach is a very effective energy absorber. This is especially significant in low lying areas such that severe storms can impact upland structures. The effectiveness of wide beaches in reducing structural damage has been demonstrated through both field studies conducted after storms and by application of accepted coastal engineering principles as discussed below.

Damage surveys following major storms have documented the storm damage reduction due to wider beaches. Figure 1a presents the results of a survey by Shows (1978) of the damage experienced by 540 structures after Hurricane Eloise which impacted the western shoreline of Florida in 1975. The "CL" shown in this plot is a permitting jurisdictional "Control Line" established by the State of Florida and is oriented approximately parallel to the shoreline. The steeply sloping damage curve is a reflection of the wave energy absorbed by the additional beach width fronting the individual structures. The effect of beach nourishment is to place a wave absorber (the beach) seaward of upland structures thereby reducing the wave heights and energies occurring at any upland location. Figure 1b presents the results of a beach nourishment project that adds 50 feet (15 m) to the beach width. The reduction in damage is evident. As an example, shifting the damage curve by 50 feet reduces the damage in Figure 1b by approximately $ 50,000 (1976 dollars) for a structure located 100 feet (33 m) from the Control Line.

Rogers (2001) has conducted an analysis of the effectiveness of six North Carolina beach nourishment projects in reducing impacts by Hurricanes Dennis and Floyd which occurred in 1999. The two categories of damage to structures were "destroyed" and "threatened by erosion", the latter generally signifying partial undermining of the foundation. The six nourished beaches included three which had been designed by the U.S. Army Corps of Engineers and which incorporated a substantial dune in the design.



(a) Average Damage per Structure vs Distance From Control Line



b) Effect of Shifting the Damage Curve by 50 ft (15 m)

Figure 1: Illustrating the Damage vs Distance From the Control Line and the Damage Reduction Resulting From an Additional 50 feet (15 m) Beach Width

The other three projects included two private projects and a beach disposal operation adjacent to a navigational channel. These latter projects were not as substantial as those designed by the Corps of Engineers and did not incorporate a dune feature. Hurricane Floyd which occurred two weeks after and was stronger than Hurricane Dennis was rated as having a 75 year return period and caused a maximum storm tide of 3 m. These two hurricanes impacted approximately 500 km of shoreline and caused 968 structures to be rated as either “destroyed” or “threatened by erosion” in the 300 mile shoreline of North Carolina. For those structures located behind the substantial dunes constructed as part of the three Corps of Engineers projects described earlier, no structures were listed in either of these two impacted categories. Although structures located landward of the other three nourishment projects did not fare as well as those protected by the three more substantial projects with dune features, it was concluded that these projects provided significant protection and damage reduction to the upland structures.

Approximate computational methods can be applied to estimate the reduction in damage potential as a result of additional beach width. Dean (2000) has applied the Dally, et al. (1985) model of wave height reduction over bathymetry/topography that can include the contribution of a beach nourishment project.

$$\begin{aligned} &\frac{\partial EC_G}{\partial y} = -\frac{K}{h}\left[EC_G - (EC_G)_S\right],\ \textit{Waves Breaking} \\ &\frac{\partial EC_G}{\partial y} = 0,\ \textit{No Breaking} \end{aligned} \qquad (1)$$

in which E is the wave energy density ($E = \rho g \frac{H^2}{8}$), ρ is mass density of water, H is the wave height, C_G is group velocity, K is a constant (taken here as 0.17), the subscript "*s*" denotes a stable value of the quantity in the parenthesis, and $H_S = \alpha\left(h+S\right)$ where α is a proportionality factor (≈ 0.4), S is the storm tide, h is the local water depth related to the mean water level and y is directed onshore. Eq. (1) has the characteristic that waves will shoal in accordance with the conservation of wave energy in the absence of breaking and that waves breaking over a uniform depth will stabilize at a wave height which is approximately 0.4 times the water depth. Waves commence breaking where the ratio of wave height to total water depth is approximately equal to 0.78.

1.3 Recreational Amenities

In many cases, coastal armoring has been constructed to protect upland structures. As noted, on an eroding shoreline, the beach width available for recreation will diminish until recreational opportunities are very limited. Nourishment can restore the recreational amenities of a beach. An example is Miami Beach, Florida where, prior to the beach nourishment project, which occurred during the period 1976 to 1981, the beach was extremely narrow and hazardous in places to walk along at high tide. As the beaches eroded, so did the tourism base and the economy of this area. The nourishment project has revitalized the economy of the area such that as of 1991, there were 20 million visitors annually to this 16 km beach which is more than twice the number of the combined visitations to the three most heavily visited National Parks in the United States. The total income attributed to the U. S. economy by beach tourists is $260 billion with $60 billion in Federal taxes (Houston, 2002).

1.4 Beaches as Habitats

Beaches also serve as habitats for several species including birds and sea turtles. Sea turtles are an endangered species in the United States and require a certain beach width for successful nesting. Coastal armoring constructed to limit coastal retreat will result in gradual narrowed beaches such that sea turtle nesting habitat is impaired. Many such beaches have been nourished in the United States and the overall effect on turtles has been favorable. In Florida, nourished beaches are monitored for three years to document effects on nesting sea turtles. If the nourishment material provides a good "match" to the native sediments, usually, there is a reduction in nesting activity for the first year after nourishment followed in later years by no discernible effect of the nourishment. A total of 316 km of so-called "index beaches" have been monitored in Florida for sea turtle nesting activity since 1989. Figures 2 and 3 present the results of this monitoring for the Loggerhead and Green Turtle species, the first and second most numerous species in Florida. On average, the Loggerhead nests are spaced at approximately 8 m along the 316 km monitored. The increase of Green turtle nests (Figure 3) is very dramatic. These turtles and their eggs were harvested for food until about 50 years ago.

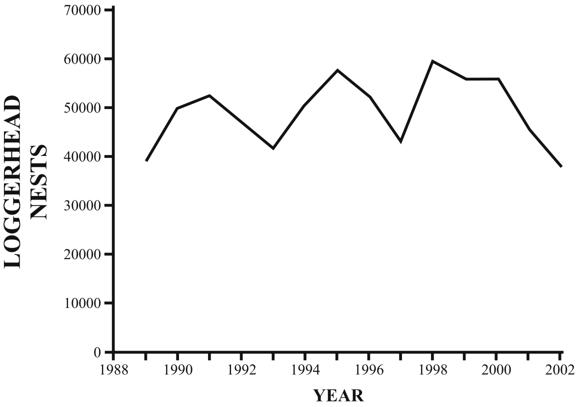


Figure 2: Variation With Time of Numbers of Loggerhead Turtle Nests Along 316 km of Florida's Sandy Shoreline

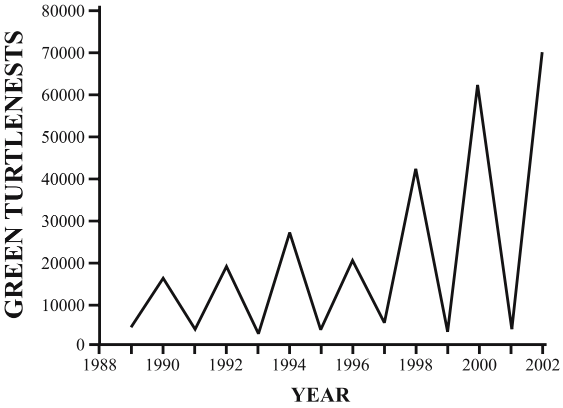
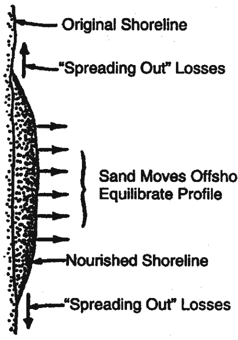


Figure 3: Variation With Time of Numbers of Green Turtle Nests Along 316 km of Florida's Sandy Shoreline

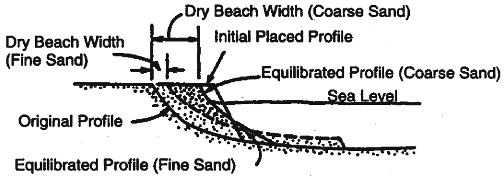
2. Sediment Transport Mechanics of Nourished Beaches

Nourished beaches respond to the same forcing as natural beaches, primarily waves, tides and associated currents. Nourished beaches represent a planform perturbation (or "bulge") and thus are out of equilibrium and the nourished profile is usually placed at a slope that is steeper than equilibrium. Thus nourishment induces both longshore and cross-shore (seaward) sediment transport components as illustrated in Figure 4.

Analytical and numerical models have been developed to represent the mechanics of the induced longshore and cross-shore sediment transport components. Longshore and cross-shore processes are usually treated separately with some justification provided by the cross-shore time scales usually being shorter than the longshore processes. The paragraphs below first review an analytical theory for the longshore processes followed by some results obtained from this theory.



(a) Plan view showing "spreading out" losses and sand moving offshore to equilibrate profile.



(b) Elevation view showing original profile, initial placed profile and adjusted profiles that would result by nourishment with coarse and fine sands.

Figure 4: Sand Transport to Adjacent Beaches and Adjusted Profiles Associated with Nourishment with Coarse and Fine Sands

2.1 The Pelnard Considère Theory

The Pelnard Considère Theory (1956) is a second order equation based on combining the equation for sediment conservation (continuity equation)

$$\frac{\partial y}{\partial t}+\frac{1}{\left(h_{*}+B\right)}\frac{\partial Q}{\partial x}=0 \tag{2}$$

with the linearized form of the following equation for longshore sediment transport

$$Q=K\frac{H_b^{2.5}\sqrt{g/\kappa}}{8(S-1)(1-p)}\sin 2(\beta-\alpha) \tag{3}$$

In the above equations, y is the cross-shore coordinate to some contour, usually mean sea level, t is time, Q is the longshore sediment transport rate, x is the longshore coordinate, h_* is the depth of closure, B is the berm height such that $\left(h_* + B\right)$ is the vertical dimension of active profile motion, K is the so-called sediment transport coefficient (dimensionless and of order unity), H_b is the breaking wave height, g is gravity, κ is the ratio of breaking wave height to breaking water depth (≈ 0.78), S is the ratio of sediment density to water density and p is the sediment porosity.

Eq. (2) considers the beach profile to be in equilibrium and to move landward and seaward in response to divergences and convergences, respectively without change of form, see Figure 5.

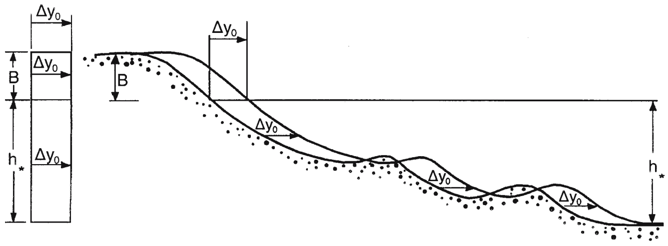


Figure 5: Profile Translation, Δy_0, Associated With Volume Density Addition, *V*, Compatible Sands

The Pelnard Considère (PC) equation is

$$\frac{\partial y}{\partial t}=G\frac{\partial^2 y}{\partial x^2} \tag{4}$$

which is recognized as the heat conduction equation. The quantity G is termed the "longshore diffusivity", has dimensions of Length^2/Time and is given by

$$G=K\frac{H_b^{2.5}\sqrt{g/\kappa}}{8(S-1)(1-p)\left(h_{*}+B\right)} \tag{5}$$

such that the longshore diffusivity is greater for larger breaking wave heights. The role of G is shown clearly by rewriting the *PC* equation in the following form

$$\frac{\partial y}{\partial (Gt)}=\frac{\partial^2 y}{\partial x^2} \tag{6}$$

such that for any project, the evolution at any time is related only to the product of time and longshore diffusivity. If two beach nourishments are constructed with scaled initial planforms of length ℓ, the following form

$$\frac{\partial y}{\partial(Gt / \ell^2)} = \frac{\partial^2 y}{\partial(x / \ell)^2} \tag{7}$$

establishes a non-dimensional time Gt / ℓ^2 and a non-dimensional length x / ℓ. Thus two projects constructed with scaled initial planforms will evolve with scaled planforms, but with rates depending on the scaled time, Gt / ℓ^2.

Many valuable approximate results can be established based on solutions to the Pelnard Considère theory as reviewed later in this paper. The interested Reader is referred to the original paper or to a number of other sources for additional results: Le Mehaute and Brebner (1961), Larson, et al. (1997) and Dean (2002).

2.2 Equilibrium Beach Profile Concepts

Under the action of constant water level and wave forcing, beaches tend to approach a constant profile, termed the equilibrium beach profile (EBP). Bruun (1954) first identified the following EBP form

$$h(y) = Ay^{2/3} \tag{8}$$

in which h is the water depth at a distance, y from the shoreline and A is a so-called profile scale parameter which depends on sediment size (or sediment fall velocity) as shown in Figure 6 and in Table 1. Because the A parameter increases with sediment size, beaches composed of coarser sediments will be steeper that those with finer sediments. EBP concepts and applications are very useful for evaluating the effects of nourishment with sediments that are different sizes than the native. As illustrated in Figure 7, depending on the nourishment sediment size, D_F, relative to the native, D_N, and volume of nourishment added per unit beach length, three types of nourished profiles are possible: intersecting, non-intersecting and submerged. Intersecting profiles require sediments that are coarser than the native; however sediments coarser than the native can result in non-intersecting profiles. Compatible sediments result in non-intersecting profiles and submerged profiles require sediments that are finer than the native. Although we will not examine the details of the applications of equilibrium beach profiles to beach nourishment, some of the results will be discussed.

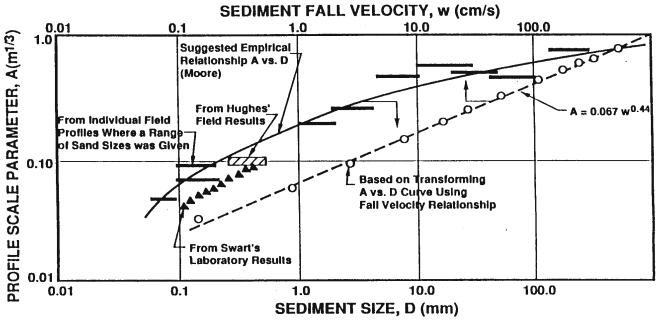


Figure 6: Variation of Beach Profile Scale Parameter, *A*, With Sediment Size, *D*, and Fall Velocity, *w* From Dean (1987)

Table 1: Variation of sediment scale parameter, *A* with sediment size, *D*

***D*(mm)**	**0.00**	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**
0.1	0.063	0.0672	0.0714	0.0756	0.0798	0.084	0.0872	0.0904	0.0936	0.0968
0.2	0.100	0.103	0.106	0.109	0.112	0.115	0.117	0.119	0.121	0.123
0.3	0.125	0.127	0.129	0.131	0.133	0.135	0.137	0.139	0.141	0.143
0.4	0.145	0.1466	0.1482	0.1498	0.1514	0.153	0.1546	0.1562	0.1578	0.1594
0.5	0.161	0.1622	0.1634	0.1646	0.1658	0.167	0.1682	0.1694	0.1706	0.1718
0.6	0.173	0.1742	0.1754	0.1766	0.1778	0.179	0.1802	0.1814	0.1826	0.1838
0.7	0.185	0.1859	0.1868	0.1877	0.1886	0.1895	0.1904	0.1913	0.1922	0.1931
0.8	0.194	0.1948	0.1956	0.1964	0.1972	0.198	0.1988	0.1996	0.2004	0.2012
0.9	0.202	0.2028	0.2036	0.2044	0.2052	0.206	0.2068	0.2076	0.2084	0.2092
1.0	0.210	0.2108	0.2116	0.2124	0.2132	0.2140	0.2148	0.2156	0.2164	0.2172

Notes:

(1) The *A* values above, some to four places, are not intended to suggest that they are known to that accuracy, but rather are presented for consistency and sensitivity tests of the effects of variation in grain size.

(2) As an example of use of the values in the table, the *A* value for a median sand size of 0.24 mm is: $A = 0.112\ \text{m}^{1/3}$. To convert *A* values to $\text{ft}^{1/3}$, multiply by 1.5.

2.3 Results From Solutions to the Pelnard Considère Equation and Application of Equilibrium Beach Profile Concepts

Several valuable results from the PC equation and solutions thereof and equilibrium beach profiles are reviewed below.

Background Erosion: Many beach nourishment projects are constructed in response to a pre-existing erosion rate, e, (here, termed "background erosion rate") which can be natural or due to anthropogenic causes. The *PC* equation being linear, establishes that the solution for a beach nourishment project can be added to the solution for background erosion, occurring separately. Denoting $y_T\ (x,t)$ as total shoreline change and $y_0(x,t)$ and $y_B\ (x,t)$ as the solutions in the absence of background erosion and only the background erosion, respectively, the following applies

$$y_T(x,t) = y_0(x,t) + y_B(x,t) \tag{9}$$

Project Longevity on a Long Straight Beach: Consider a project with initial rectangular planform of length, ℓ, constructed on a long straight beach with no background erosion. It can be shown that the time required for a certain percentage, $X\%$ of the volume to be transported out of the nourishment area (Figure 4a) can be represented by

$$t_{X\%} = K_{X\%} \frac{\ell^2}{H_B^{2.5}} \tag{10}$$

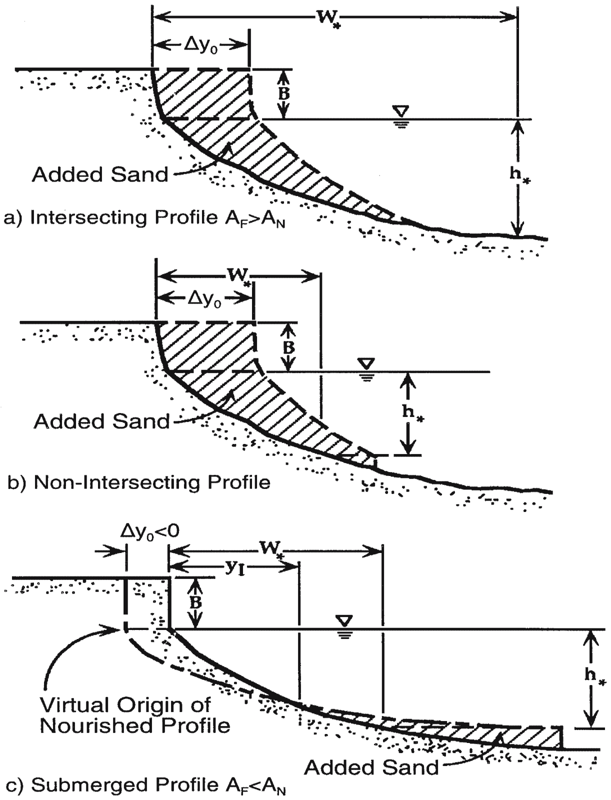


Figure 7: Three Generic Types of Nourished Profiles. Adapted from Dean (1991)

As an example consider $X = 50$, such that the result pertains to 50% of the volume remaining within the nourishment area, The quantity $K_{50\%}$ is

$$K_{50\%} = 0.18 \text{ years } \text{m}^{2.5} / \text{km} \tag{11}$$

such that the time t is in years, the project length, ℓ is expressed in kilometers and the breaking wave height, H_B is in meters. This relationship demonstrates the significance of project length. As an example, the time required for a project with length, $\ell = 1$ km, acted upon by a breaking wave of height of 1 m to "lose" one-half of its volume to the adjacent beaches is 0.18 years, approximately two months. If the same wave height acted on a nourishment project with a length of 10 km, the half-life would be 18 years! Of course, if a background erosion was present in the nourishment area as is usually the case, Eq. (10) would require modification. However, we have seen that we could address the background erosion through superposition.

Independence of Project Evolution to Storm Sequencing: It can be shown from the *PC* equation that the evolution of a project depends only on the cumulative wave loading, that is the evolution is independent of the sequencing of storms that caused the evolution, and only depends on the cumulative wave energy flux on the project up to a particular time.

Existence of a Representative Wave Height: Although in nature, waves vary with time, at any time the evolution of a project can be shown to be same as if a particular constant wave height had acted on the project. This equivalent wave height, H_{eq}, is expressed as

$$H_{eq} = [(\overline{H_B^{2.5}})]^{0.4} \tag{12}$$

Increasing Renourishment Intervals: For the case of no background erosion or weak background erosion, the required renourishment intervals to maintain a certain minimum volume within the nourishment area increase with renourishment number. The explanation for this is that as the earlier nourishments evolve, they behave as longer and longer projects and thus evolve more slowly with time. The overall evolution rate therefore decreases with time and renourishment number. Somewhat surprisingly, for quite high background erosion rates, the required renourishment intervals decrease with time although the explanation is more complicated than is warranted for presentation here.

Stationary Project Centroid For Compatible Sediments: The evolution of nourishment projects constructed with sand compatible with the native sediments on a long straight beach are surprisingly insensitive to wave approach angle. This result is very valuable to the designer of beach nourishment projects on long straight beaches as it allows the designer to concentrate efforts on quantifying the wave height characteristics, which are usually better known than the wave directions. Usually, the effects of wave direction will simply reduce the evolution rate moderately.

Planform and Total Plan Area Evolution Resulting From Nourishment With Sand Compatible With or Coarser or Finer Than the Native: It has been noted that nourishment with compatible sand results in a planform anomaly centroid that is stationary. If the nourishment sand is finer or coarser than the native, the centroid anomaly migrates updrift and downdrift, respectively.

In addition to affecting the planform centroid, equilibrium beach profile (EBP) concepts can be applied to investigate the effects on the total planform resulting from nourishing with sediments compatible with or coarser or finer than the native. Total plan area as referenced here is the sum of the dry beach areas inside and outside of the project area. Nourishment sands coarser than, compatible with and finer than the native evolve with increasing total plan areas, constant total plan areas and diminishing total plan areas, respectively. Here, the initial total plan area is considered to be that subsequent to equilibration.

3. Two Case Examples of the Performance of Beach Nourishment Projects

With some of the methodology available to examine the performance of beach nourishment projects presented and a discussion of some of the results, it is useful to compare the evolution of two beach nourishment projects with predictions. For this purpose, we have developed guidance for beach nourishment design in Florida that can be applied to predict the long term performance of the projects in advance of their construction. The guidance consists of specification of parameters along the sandy portions of the Florida coastline, including effective wave height (as defined in Eq. (12)), effective wave period, depth of closure, etc. As an example, Figure 8 presents the recommended distribution of effective wave height along Florida's sandy shores. Available space in this paper does not permit presenting the other design variables; however, their availability allows performance predictions to be made without any calibration. The rationale is that as the performance of projects becomes available through monitoring, comparison with an established framework and without calibration will eventually amass enough information to fine-tune the recommended parameters as necessary. By contrast, if calibration were carried out on a case by case basis, it would not be possible after a period of time to know which of the parameters (or methodology) was causing the need for calibration. The following sections will present comparisons of monitoring with predicted performance for two nourishment projects applying the methodology described in Dean and Yoo (1992).

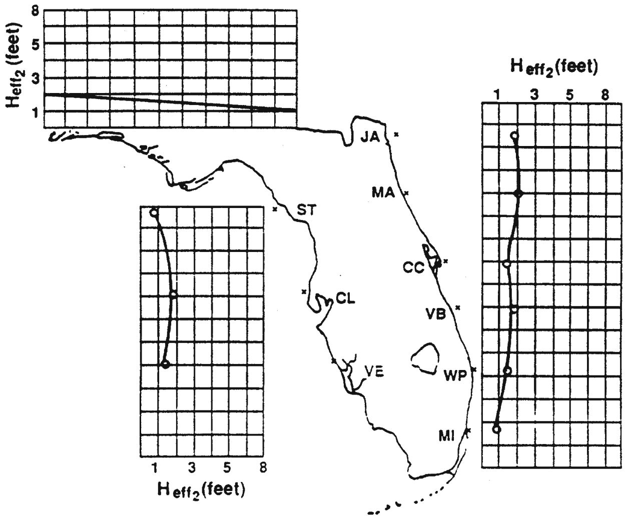


Figure 8: Effective Wave Height Variation Around the State of Florida
(Note: 3.28 feet = 1 m)

3.1 Delray Beach, Florida

This project was constructed initially in 1973 after attempts to protect a coastal highway with revetments failed twice. The nourishment history is shown in Table 2 and comparisons of the measured and predicted performances is presented in Figure 9 where background erosion rates of zero and 2 feet per year (0.6 m/year) are shown.

Three features of Figure 9 merit discussion: (1) There is reasonably good agreement between the measurements and predictions, (2) There are times when the predictions overpredict the performance and other times when the performance is underpredicted. This is due, in part, to the variability in wave conditions (primarily wave height which mobilizes the sediment and drives the evolution). Due to this variability, a single wave height can only be correct on average for representing the long-term forcing, and (3) Some surveys indicate more volume within the project area than preceding surveys, even in the absence of beach nourishment in the intersurvey period. The theories that have been discussed are unable to predict this increase. The two possible explanations for this increase include sand waves which are known to exist in the nearshore but for which there is not a complete understanding or simply survey errors.

Table 2: Nourishment History at Delray Beach, Florida

Nourishment Date	Volume Added (Millions of m^3)	Cumulative Volume Added (Millions of m^3)
1973	1.25	1.25
1978	0.54	1.79
1984	0.99	2.78
1992	0.79	3.57
2002	0.78	4.35

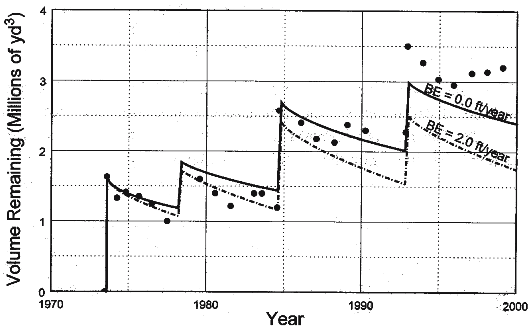


Figure 9: Comparison of Measured and Predicted Performance of Delray Beach, FL Beach Nourishment Project

3.2 Perdido Key, FL

Perdido Key, Florida was nourished in 1989 with 4.5 million m^3 over a length of approximately 7 km. In addition, approximately 3 million m^3 of sand was placed in water depths of approximately 6 m. As seen in Figure 10, this project is situated adjacent to a deepened inlet (Pensacola Pass) which complicates the analysis considerably. Monitoring results are available for approximately 8 years. The Project area is shown in Figure 10 and the measured volumetric evolution within the project area is compared with the predicted project evolution in Figure 11.

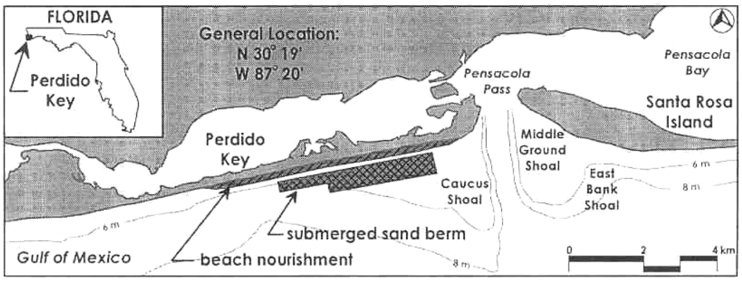


Figure 10: Project Area and Nourishment on Perdido Key, FL

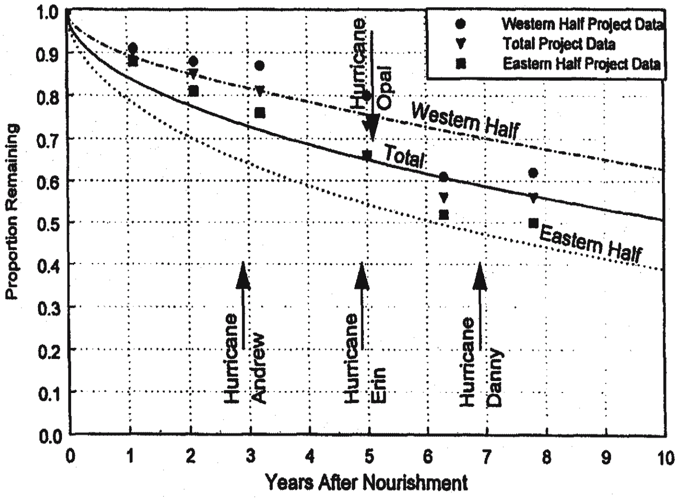


Figure 11: Comparison of Measured and Predicted Volumes Remaining Within Project Area for Perdido Key Beach Nourishment Project. The Lines and Symbols Represent Predictions for the two Project Halves and the Total Project

This project adjacent inlet was considered as a sink in the formulation, that is, the shoreline was assumed "pinned" at the inlet (eastern end of the Project). This results in an asymmetric evolution with more rapid losses from the Project area for the eastern half than for the western half. Also of interest is that during the eight years of monitoring, this area was subjected to a fairly large number of hurricanes and tropical storms, with some of them being rather severe. Since the predictions agree reasonably well with the measurements, it is likely that the specified effective wave height for this project is too large for average conditions.

4. Summary

Of the available methodologies for addressing beach erosion, beach nourishment is the only “environmentally friendly” approach which can both provide protection to upland structures and maintain a beach that is suitable for recreation and natural habitat, such as for sea turtles. Beaches are also valuable for recreation and in areas of favorable climates and warm water, can provide a valuable source of income to the local economy.

Design of beach nourishment projects usually considers the alongshore sediment and cross-shore sediment transport separately due, in part to the shorter time scale for the cross-shore sediment transport.

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