CHAPTER 326

WIND BLOWN SAND AT CASTROVILLE, CALIFORNIA

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ABSTRACT

This paper reports the results of a study designed to evaluate the performance of a set of aeolian transport models, including moisture content corrections, as tested against field measurements. Empirical data were obtained during experiments conducted near Castroville, California, in January, 1993. The comparisons show that the Lettau and Lettau (1977) transport model, coupled with the Belly (1964) moisture correction model, produces estimates most closely approximating measured rates. Nevertheless, the advantages of this approach relative to using an "uncorrected" Bagnold model are small.

INTRODUCTION

Aeolian sand transport is an important component of the sediment budget of many coastal environments. Blowing sand may represent a hazard (Sherman and Nordstrom, 1994) or a resource, especially with regard to dune building and habitat creation (Carter, 1988). For these reasons, it is important to model the aeolian system in a manner consistent with the needs of coastal engineers and resource managers. From a geomorphological perspective, an understanding of the nature of aeolian systems yields insight into fundamental aspects of sediment transport and resulting

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landform change. Determining which model constitutes the most accurate and physically-meaningful approach to aeolian flux prediction is, therefore, a critical challenge.

A number of models have been developed for the purpose of predicting aeolian sand transport rates (see summary by Namikas and Sherman, in press). Those of most practical interest are based on a common set of assumptions: the wind is steady, uniform, and blowing across an unobstructed, horizontal surface of clean, dry, homogeneous sand. These conditions describe the most basic transport systems that one can posit. Models developed from these assumptions have been discussed extensively elsewhere (e.g., Anderson et al. 1991; McEwan and Willetts 1994; Lancaster 1995), and their derivations are not reviewed here. We note, however, that the idealized conditions they describe are seldom, if ever, appropriate to coastal environments. Complicating effects of sediment moisture content and surface slope, in particular, may exert considerable control on the behavior of the transport system.

Previous field experiments aimed at matching observed and predicted transport rates have usually found poor correspondence. Some successes have been reported in cases where empirical constants have been adjusted to improve the model's performance. Because such adjustments are usually site specific, they are of relatively diminished utility when little is known about the transport environment or where field work is impractical. Indeed, if we are always forced to perform field experiments to calibrate the equations, the practical value of modeling is severely constrained. The purpose of this paper is to report the predictive performances of several transport models, in light of field data and in consideration of slope effects and adjustments for moisture content. The objective is to test the models as they appear in the literature and as they might be employed in an engineering or management context.

MODEL DESCRIPTION

Several previous efforts at comparing observed and predicted transport rates have been reviewed recently by Sherman et al. (in press). Typically, these have omitted slope and/or moisture effects, have used liberally the empirical constants in the models, or have been predicated on potentially flawed experimental designs,. The Sherman et al. study suggests that, of the five models tested, the best statistical explanation (of the order of 20%) was afforded by the Bagnold (1936) and Zingg (1953) models. These two equations are essentially the same, varying only in the selection of the constant. Their conclusions point to the necessity for similar comparative studies using high quality data sets from other environments.

In the present study, we test the transport models of Bagnold (1936), Kawamura (1951), and Lettau and Lettau (1977). They were selected in conformity with the findings of Sherman et al. (in press) and because they are commonly used in coastal applications. We also considered the moisture-content correction equations of Belly (1964), Hotta et al. (1984), and Kawata and Tsuchiya (1976). For all tests, we assumed a sediment density, ρ_s, of 2650 kg m^{-3}, an air density, ρ, of 1.23 kg m^{-3}, and a gravity constant, g, of is 9.8 ms^{-2}. Sediment flux, q, is in kg m^{-1} s^{-1}. A brief description of the models follows.

One of the most frequently used models to predict transport rates is that of **Bagnold (1936)** who suggested that:

$$q = C\sqrt{\frac{d}{D}}\,\frac{\rho}{g}\,u_*^3 \tag{1}$$

where C is a surface-sediment-dependent constant ranging in value from 1.5 to 3.5 (C = 1.8 for typical dune sands and this value is used here), d is mean grain diameter, D is a reference grain diameter of 0.25 mm, and u_* is shear velocity.

Kawamura (1951) proposed a model that includes an explicit threshold shear-velocity term, u_{*t}.

$$q = C\frac{\rho}{g}\,(u_* - u_{*t})\,(u_* + u_{*t})^2 \tag{2}$$

In this expression, C = 2.78, and we adopt this value even though Horikawa et al. (1984) suggest that C = 1.0 might be better.

Lettau and Lettau (1977) proposed an expression with some of the attributes of both previous models:

$$q = C\sqrt{\frac{d}{D}}\,\frac{\rho}{g}\,(u_* - u_{*t})\,u_*^2 \tag{3}$$

where C in this case has a value of 4.2.

The Kawamura (1951) and Lettau and Lettau (1977) models require the threshold shear velocity to be estimated according to local sediment size characteristics. Bagnold (1936) suggested a Shields-type relation for u_{*t} of the following form:

$$u_{*t} = A\sqrt{gd\left(\frac{\rho_s - \rho}{\rho}\right)} \tag{4}$$

where A is a constant (assumed to be 0.085 during saltation).

When moisture is present in the interstices of surface sands, the resulting surface tension acts as a cohesive force. The shear velocity required to entrain sediments must therefore increase (e.g., review by Namikas and Sherman 1995). We considered three models developed to account for increased threshold shear velocity as a result of moisture content, u_{*tw}.

Belly (1964) proposed an empirical model based upon his wind tunnel experiments:

$$u_{*tw} = u_{*t}(1.8 + 0.6 \log_{10} w) \quad \textbf{(5)}$$

where w is percent moisture content by weight. This model applies to conditions where w does not exceed 4%.

Kawata and Tsuchiya (1976, described in Hotta at al., 1984) developed a model based upon direct consideration of the surface-tension-force distribution between particles:

$$U_{*tw} = U_{*t}\sqrt{1+B} \quad \textbf{(6)}$$

where

$$B = \frac{2\sqrt{6}}{5}\sqrt{\alpha_1\alpha_2}\sqrt{n_o}\sqrt{\frac{\rho_s}{\rho_w}\frac{T\sqrt{w}\cos\xi}{(\rho_s - \rho)gd}} \quad \textbf{(7)}$$

and α_1, α_2 are constants, n_o is the number of grain contact points, ρ_w is density of water, ξ is the water/grain contact angle, and T is the surface tension of water.

Hotta et al., (1984) proposed a wind-tunnel-derived empirical relationship for moisture effects:

$$U_{*tw} = U_{*t} + 7.5w \quad \textbf{(8)}$$

The prescribed applicability range for this model is 2% to 8% moisture content and sediment sizes between 0.2 mm and 0.8 mm.

In order to obtain the information necessary to evaluate the above models against prototype conditions, measurements or derivations of the following parameters are required: shear velocity, surface slope, mean grain size, transport rate, and moisture content. In order to attribute differences between observed and predicted transport rates to model performance, substantial care must be taken in experimental design. A field study was designed with the aim of obtaining suitable data.

STUDY SITE

Field experiments were conducted at a site along the coast of Monterey Bay, approximately mid-way between Santa Cruz and Monterey, near the town of Castroville. The site is exposed to open-ocean winds and waves from the southwest to northwest, and aeolian activity is therefore common. Instruments were deployed on the upper, flat portion of a well-developed, high-tide berm (Figure 1) fronting a small foredune system that is essentially continuous from the mouth of the Salinas River (to the south of the site) to Moss Landing (to the north). The upper foreshore is relatively steep and often cuspate, and it descends to a much flatter low-tide terrace merging, seaward, with bar topography that is periodically punctuated with rip channels. Morphodynamically, the system falls into the reflective regime during high tide and the dissipative regime during low tide stages. Spring high tides are often associated with foredune scarping and the deposition of flotsam (mostly kelp and woody debris) on the berm flat. Additional details of this site are described in Bauer et al. (1990) and Bauer (1991).

Figure 1: Castroville study site with instrument array.

EXPERIMENTAL DESIGN

Field experiments were conducted over a 30-day period in January, 1993. Only the January 13 data are presented here because this day had the longest duration of continuous sand transport during the study period. Further, winds were blowing nearly parallel to the shore so that it is reasonable to assume that local equilibria between the velocity profiles and the saltation system existed--that is, conditions were as close to ideal as one might expect for a beach environment. This eliminates complications arising from potential fetch effects (e.g. Nordstrom and Jackson 1992), or from internal-boundary-layer development (e.g. Bauer et al. 1996). Measurements began at 05:45 (PST), and continued for about the next five hours. A total of five data runs were completed, each with three to five u_*-q pairings.

Five sampling locations were established across the berm at 5 m intervals (Figure 2). Gill-type, three cup anemometers were hardwired to a PC-based data acquisition system. All sample runs were of 15 minute duration, with sampling at 1 Hz. Tower 1, near the toe of the foredune, had anemometers at elevations of 0.25, 0.5, 1.0, 2.0, 3.0, and 4.0 m above the sand surface. Towers 2, 3, and 4 had anemometers at 0.2, 0.6, 1.2, and 1.8 m. Tower 5 had anemometers at 0.15, 0.3, 0.6, 1.2, 1.8, and 2.4 m. The lowest Tower 5 anemometer was disabled during this experiment. Wind vanes were installed at the tops of Towers 1 and 5. A set of cylindrical sand traps was deployed adjacent to each tower. Moisture samples were taken at Towers 1 and 3 throughout the experiment, and at Tower 5 only near the end of the data collection, by taking scrapings from the upper 3-5 mm of the sand surface. Topographical slope was measured by rod and level survey.

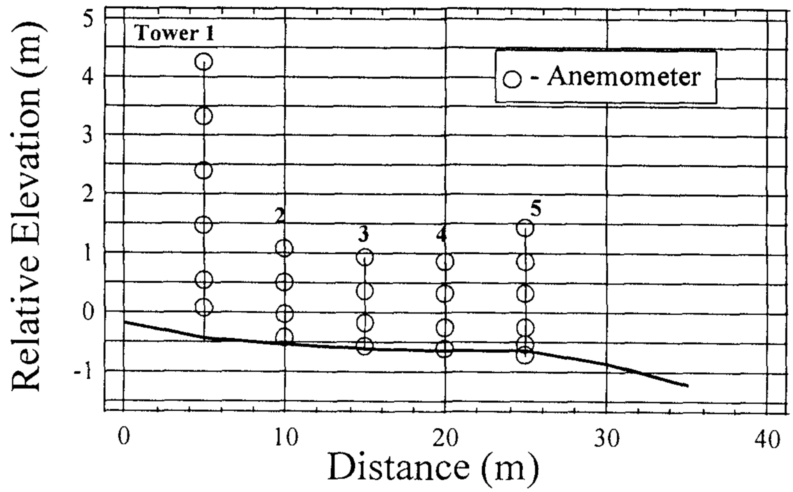

Figure 2: Instrument configuration on January 13, 1993.

Shear Velocity estimates were obtained through analysis of vertical wind-speed profiles. Linear regression was used to obtain "best fit" profile slopes, s, following the methodology described in Bauer et al. (1992). Assuming that the law of the wall applies, estimates of u_* were made using the relationship $u_* = \kappa s$, where κ is von

Karman's constant. To increase the statistical confidence of the u_* estimates, we restricted our analysis to instances where the R^2 associated with the best fit line was greater than 0.98.

Grain Size statistics were estimated using sand samples taken from the sediment traps. Samples were washed, dried, and sieved at 0.25ϕ intervals, and the data were processed according to the method of moments.

Moisture Content was estimated on the basis of pore-water weight relative to dry weight of the sediment sample. Samples were weighed, oven dried, and reweighed in order to solve:

$$w = 100 \left(\frac{W_t - W_d}{W_d} \right) \quad (9)$$

where W_t is total sample weight and W_d is the dry weight of the sample.

Sediment Transport Rates were measured with cylindrical traps (Leatherman 1978; Rosen 1978). Traps were opened for 15-minute periods to correspond with wind sampling. Trapped sands were oven dried and weighed to obtain the transport rate data.

RESULTS AND MODEL EVALUATION

Grain size estimates were obtained from a total of 19 samples taken during the transport event. Grain-size statistics were surprisingly consistent over the entire measurement period with a mean 'd' of 0.12 mm and a standard deviation of 0.007 mm. **Moisture content** was also almost constant, with a mean 'w' for the data set of 6.9 % and a standard deviation of 0.7 %. **Surface slope** upwind of the instrument array was negligible, largely because the predominant wind fetch was oriented parallel to shore. Three shore-parallel lines were surveyed upwind of the instrument array, and they indicated a maximum relief of the berm flat of less than 0.3 m over a 50 m transect. Common slope-correction models indicate that such minor relief affects predicted transport rates by less than 1%. This value is much less than our confidence level for other measurements and estimates, and therefore, we did not investigate slope effects further. **Sediment transport rate** measurements were also obtained for 19 samples. In a recent field experiment, Greeley et al. (1996) found that the efficiency of the cylindrical traps is approximately 30%. Based on that finding, we adjusted our measured transport rates uniformly by 300%.

Our first evaluation was to test the three transport models without moisture (or slope) corrections. Comparison of observed and predicted rates are presented in Figure 3. It can be seen that the Kawamura model over predicts substantially, while the Bagnold and Lettau and Lettau models fit the observations relatively well. There is very little difference in the degree of statistical explanation associated with each model. With the Bagnold model, $R^2 = 0.50$; for Kawamura, $R^2 = 0.48$; and for Lettau and Lettau, $R^2 = 0.50$. The main difference between the model performances are associated with the slopes and offsets of best-fit lines.

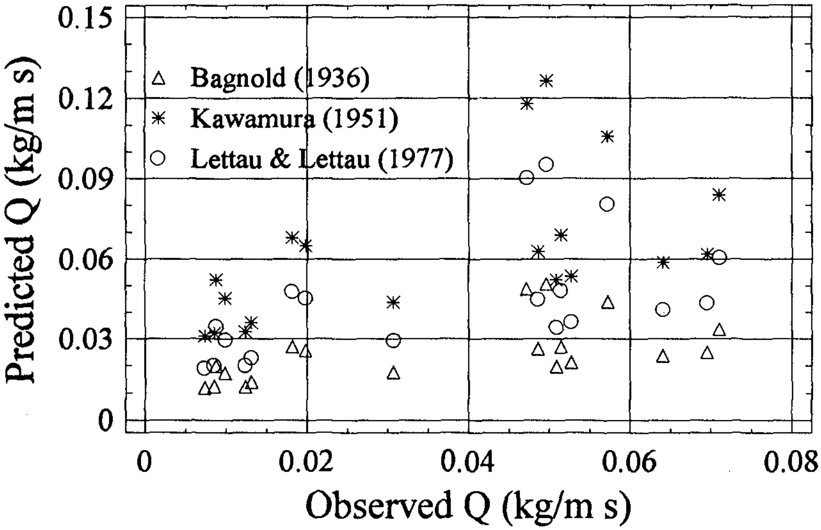

Figure 3: Comparison of observed and predicted transport rates without moisture content adjustments.

A second comparison incorporating moisture-content corrections was made. We evaluated the three moisture models described above (Equations 5 - 8) for their viability with the field data. In several instances, both the Hotta et al. and Kawata and Tsuchiya models yielded predictions of 'no transport' when our measurements clearly showed sediment movement. This peculiar situation arises when the threshold shear velocity predicted by these models on the basis of moisture content is greater than the observed shear velocities. We decided that this was one rational basis upon which the viability of the moisture models, vis-a-vis field data, could be distinguished. Since only the Belly (1964) model was immune to this problem, we used it with the transport equations. Note, however, that because there is no explicit threshold term in the Bagnold model (it is implicit in the parameterization of shear velocity), it was not considered appropriate to apply a moisture correction factor to his equation. Therefore, only the Kawamura and Lettau and Lettau models, with the Belly modification, were compared. Figure 4 shows that there is still considerable scatter in the relationship, with the main effect of accounting for moisture content being an overall reduction in predicted transport rate.

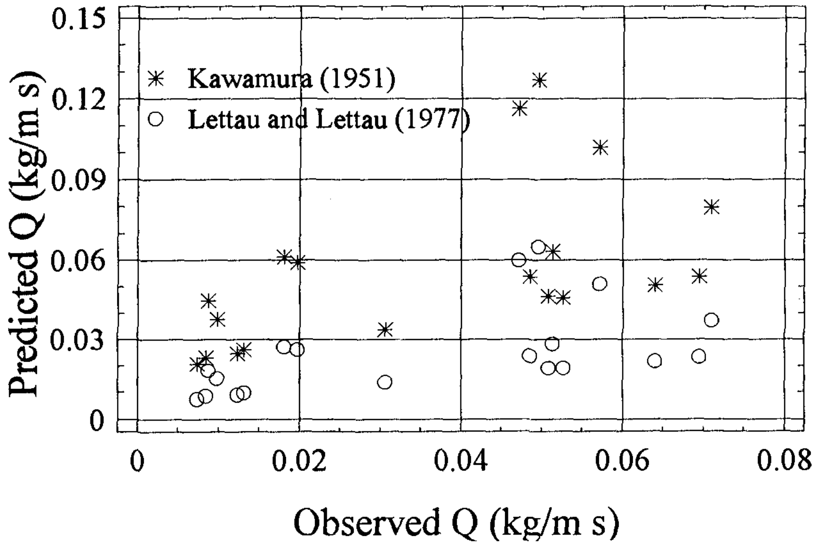

Figure 4: Comparison of observed and predicted transport rates using the Kawamura and Lettau and Lettau models with Belly's moisture model.

Linear regression was used to determine the statistical association between observed and predicted transport rates. On a log-log plot, R^2 for both models was 0.50. However, the Lettau and Lettau/Belly combination yielded predictions that were closer to a one-to-one correspondence with observations. This is best illustrated in Figure 5 using probability density plots (normalized frequency of occurrence) that compare smoothed distributions of ratios of predicted to observed values for both

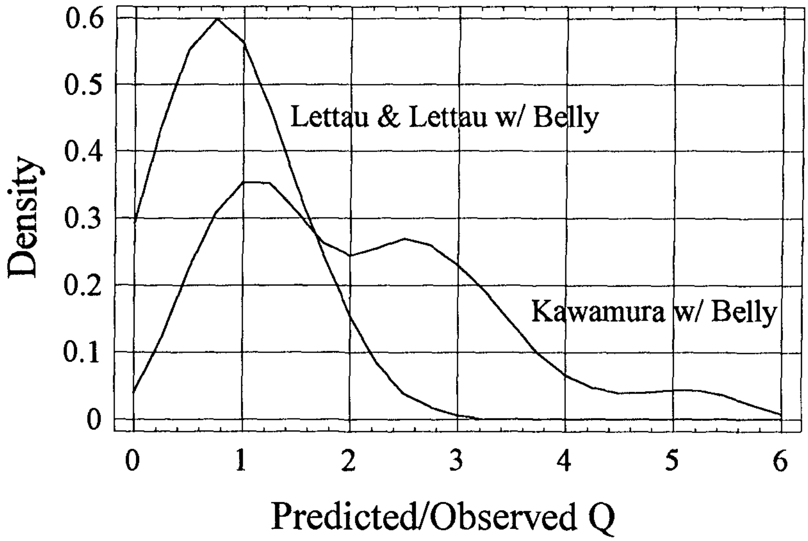

Figure 5: Comparison of ratios of predicted to observed transport rates.

models. An ideal model would have a narrow, peaked distribution centered around one--indicative of a near-one-to-one match between model and prototype conditions. Figure 5 shows that the Lettau and Lettau model, including the moisture content correction, approaches this ideal distribution, whereas the Kawamura and Belly combination over predicts substantially. These distributions of pairwise ratios of observed to predicted transport rates, coupled with the regression analysis, may represent one of the least ambiguous tests of comparative model performances.

DISCUSSION

All statistical comparisons between predicted and measured transport rates show that the scatter around a linear regression fit is approximately the same, regardless of transport model and moisture-content correction (R^2 values range from 0.48 to 0.50). Presumably, this reflects the similarity of the underlying physical bases for the models, and the fact that the variability in sediment moisture content during our experiments was small enough that the Belly model essentially acted as a near-uniform offset in the predictions--that is, all predicted transport rates were approximately uniformly reduced in magnitude.

It is encouraging that, under the conditions reported here, approximately half of the statistical variability in the transport rates monitored can be explained by the models evaluated. The uncertainty regarding the other half of the variability can be ascribed to several sources. First, our estimates of shear velocity were based upon line fitting procedures that, by their very nature, incorporate some degree of statistical uncertainty. Although this uncertainty has been minimized by excluding all wind profiles where R^2 was less than 0.99, it is not totally eliminated (e.g. Bauer et al. 1992). Because errors in estimates of u_* are compounded in the transport models (because third powers of shear velocity are used), 10 % errors translate to about 30% errors in predicted transport rates.

Second, there is substantial uncertainty associated with the measurement of sediment flux using cylindrical-type traps. We implemented a first-order correction to our measurements based on the findings of Greeley et al. (1996), but this is a crude adjustment that forces us to presume that trap efficiency is constant for the range of transport rates. This remains a point of contention.

Third, we feel some degree of unease with the universality of the models themselves and their underlying assumptions concerning grain-size distributions (only mean values are used, and sorting effects are ignored) and the steadiness of the wind field (steady-state conditions are assumed). We are also unable to make substantive distinctions among the physical--theoretical foundations of the different approaches which might provide guidelines as to their applicability. Thus, we are left with statistical performance assessments only.

It is noteworthy that whereas the use of the Lettau and Lettau model with

Belly's moisture correction provides the best predictions of transport for the Castroville system, the results are only marginally better than those obtained using the simple Bagnold model. Figure 6 compares the probability density distributions for the two approaches--the models perform almost identically for this range of conditions. The over-predictions obtained using the Kawamura model may also reflect the use of C = 2.78, instead of the more conservative estimate of 1.0 recommended by Horikawa et al. (1984). The latter value brings the Kawamura results into much closer correspondence with the other models and with our observations.

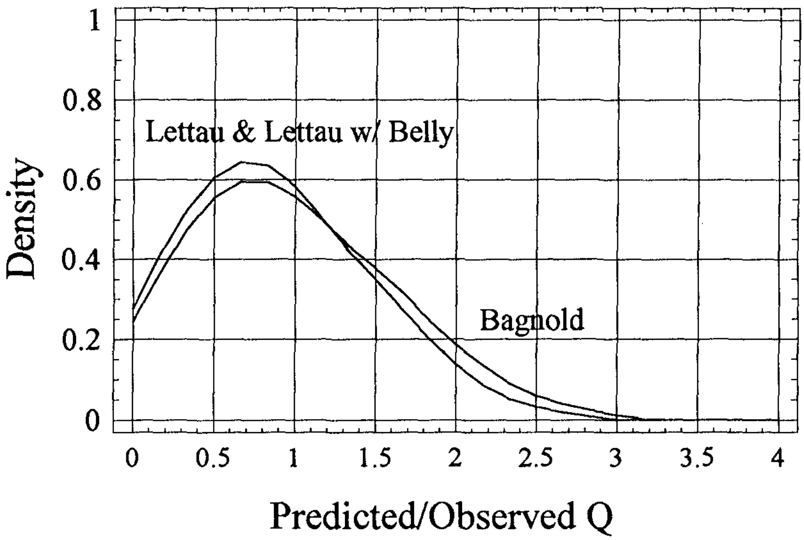

Figure 6: Comparison of ratios of predicted to observed transport rates.

Our results also compare favorably with those of Sherman et al. (in press). In that study of across shore transport conditions, the best models (Bagnold and Zingg) explained only about 20% of the statistical variability found in the observations. The Kawamura and Lettau and Lettau models each accounted for about 15% of the variability in prototype transport rates.

CONCLUSIONS

Conclusions that arise from this study include:

1. Under conditions of relatively uniform slope, grain size, and sediment moisture content, either the Bagnold, Kawamura (with C = 1.0), or Lettau and Lettau models provide reasonable estimates of aeolian sand transport. The performance of the Lettau and Lettau model can be enhanced through its coupling with the Belly moisture

model. Any of these model combinations is able to explain about 50% of the variability in transport rates observed during this part of the Castroville experiments.

2. We believe that it is possible, with carefully designed field experiments, to obtain process data of a quality comparable to that obtained in the laboratory. Nevertheless, continued uncertainty regarding the performance of field instrumentation in general and sediment traps in particular confounds our ability to assess accurately aeolian processes across beaches. The inherent complexity of natural systems may never be captured completely.

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Heavy surf at Golden Gate Park, San Francisco, California.
Photo courtesy of Robert L. Wiegel.

PART V

Coastal, Estuarine and Environmental Problems

Fisher Island adjacent to Miami Beach, Florida. Photo courtesy of Olsen Associates, Inc.