PERSPECTIVES

LONGSHORE DRIFT: TRAPPED IN AN EXPECTED UNIVERSE

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"In the face of uncertainty we must, of course, make a judgment, even if only a tentative and temporary one. Making a judgment means we create a mental model or an expected universe." Charles Perrow in "*Normal Accidents*" (1999)

ABSTRACT: **On the basis of a review of current practice in coastal science and engineering with regard to *quantitative* determination of longshore drift, we conclude that coastal scientists and engineers have been trapped in an *expected universe* of longshore-transport sand volumes without critical assessment of assumptions made in pioneering studies. As a result, workers in this field have come to accept a range of sand volumes and a range of techniques to measure or predict these volumes, stabilized by opinion of the leading experts. The shortcomings of previous studies and subsequent practice, however, indicate that these transport volumes and techniques may well be wrong. Certainly at present we have no dependable, verifiable, and consistent field measure of net or gross instantaneous or annual longshore transport volumes against which predictions can be compared.**

Both field measurements and mathematical model results, especially as used for applied purposes and expressed in annual terms, are suspect for a number of reasons. These include questionable assumptions that lag far behind our current understanding of shoreface processes, "fudge factor" coefficients for equations, the lack of storm transport measurement, and a cascade of uncertainties that moderate current practice. Once determined, annual longshore-transport sand volumes tend to be long-lived and in all cases are unverifiable by field measurement. More fundamentally, the question is raised whether an earth surface system as complex and variable as longshore transport on beaches can ever be *quantitatively* modeled or measured successfully. *Qualitative* mathematical modeling remains a valid and useful approach to understanding the nature of sedimentary processes.

INTRODUCTION

Longshore drift or littoral drift, a term used to refer to the movement of sediment in a shore-parallel direction, is variously defined. The process of sediment movement alongshore results from obliquely onshore currents generated by the activity of a combination of wave motions (primary and secondary), currents (of wind, tidal, and wave origin) on the underlying sea floor, which is composed of a variety of materials and which exhibits variable topography. Eolian transport on beaches also contributes to longshore transport. Longshore drift takes place in the supratidal and intertidal beach, swash zone, surf zone, and nearshore zone. The zone of active transport is dependent on the nature and vigor of the active processes at any given time. The parameterization of these factors is not simple, and all are spatially and temporally variable. Furthermore, there exists feedback between the processes that drive longshore drift and the morphology that arises from such transport (e.g., Russell and McIntyre 1976; Anthony 1995).

Krumbein long ago (1963) presented a conceptual diagram of beach processes (Fig. 1) that recognized many of these factors and interactions. His work provided the foundation that guided longshore transport research over the ensuing 40 years. It identifies beach geomorphic change to be caused by the interaction of energy, material, and topographic factors. Any change in morphology has a feedback relationship to each of these factors.

Interest in longshore transport arises from its sedimentological and geomorphic role on shorelines. Its consequent importance in coastal erosion and accretion has inspired considerable coastal engineering interest in the subject (Komar 1976), and a variety of techniques have been employed to attempt to measure longshore transport (Dugdale 1990). The need in engineering practice to quantify longshore drift by the development of theoretical and modeling techniques outstripped scientific progress in its understanding. Nonetheless, these engineering approaches have gained such widespread usage that they now act as an impediment to enhanced understanding of the subject. Model simplifications (e.g., shoreface profile of equilibrium, depth of closure) have become accepted scientific truths, which they are not.

In this paper we review contemporary approaches to the measurement and prediction of longshore transport. We highlight the lack of progress in understanding the subject and cite the widespread acceptance of outdated approaches and studies, coupled with (and partly sustained by) societal needs for quantification of longshore drift as major causes of this inertia. Further, and more fundamentally, we contend that lack of progress pertains to problems of cognition of the longshore transport system as well as its complexity. It is concluded that the complexity of the process defies quantitative prediction. Acknowledgment of this would enable research into longshore transport to proceed unencumbered by unattainable goals.

Many advances in science are made incrementally as existing concepts and approaches are refined and improved. There is an equally important role for reflective science that appraises what has gone before and seeks lessons for the future in examining the record of a discipline over a period of time. Only such an approach can provide critical appraisal of progress and provide the impetus for fundamental reappraisal—without it science may never look back. This is our aim in this paper. We believe, on the basis of this review, that longshore-transport research is going in the wrong direction. Continuing incremental research is not capable of turning the subject around.

MODELING OF COASTAL PROCESSES

Mathematical models of sedimentary processes are used to answer both qualitative and quantitative questions. In the first case, *qualitative models* answer the questions "why," "how," and "what if." In the second, *quantitative models* address "where," "when," and "how much" (Thieler et al. 2000). These correspond, respectively, to the *logical models* and *temporal models* of Oreskes (2000).

It is important to distinguish between the two types of models. We believe in general that the use of models in pursuit of qualitative questions is valid and useful and is an excellent way to deepen understanding of natural processes (e.g., Brocchini 1997). Quantitative models of sedimen-

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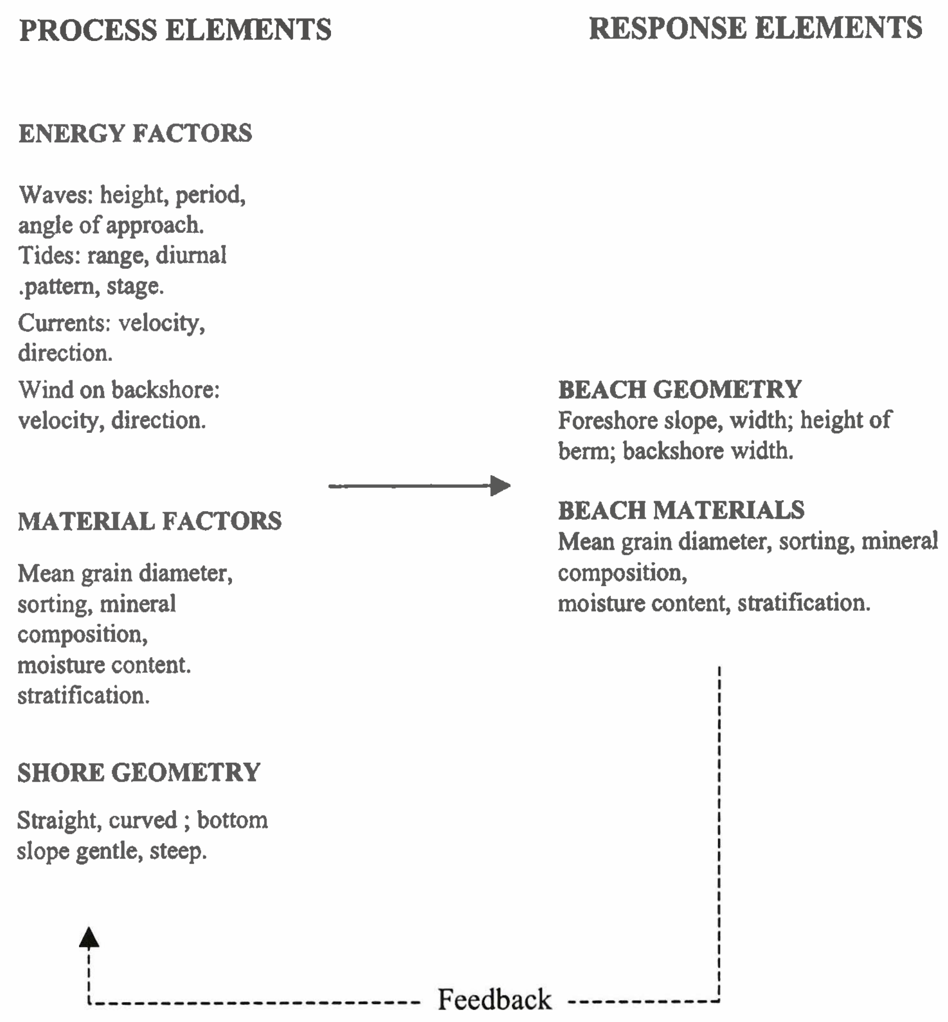

FIG. 1.—The conceptual model of the coastal system illustrating process and response elements and feedback between the two (After Krumbein 1963). This model is still a useful characterization of the process.

tary processes exercise the insight we already have to solve a societal problem. Whether such models can provide the accuracy usually needed for engineering purposes for example, is questionable.

There are many examples of the use of mathematical models of beach behavior to answer the "why," "how," and "what if" qualitative questions on large to small scales. Hequette et al. (2001) use a numerical model to explain and predict the role of shore morphology (bluffed versus unbluffed shorelines) on the storm responses of beaches in the Canadian Arctic. Werner and Fink (1993) modeled formation of beach cusps and Ashton et al. (2001) presented a theory for the origin of coastal features including the Carolina Capes, both based on mathematical models of nearshore processes. Storms et al. (2002) used numerical models to simulate evolution of barrier islands on geologic time scales.

A much larger literature that exists in scientific and engineering journals (some quoted below) attests to the widespread use of quantitative mathematical models of beach behavior in coastal science and engineering. These models focus on quantification of longshore sediment transport and obtaining a useful answer for making specific decisions such as how wide and high to build a nourished beach, how often it will need to be renourished, and on the design and impact assessment of coastal engineering structures.

Mathematical models of the two types are entirely different in terms of objectives, modeling expectations, and comprehensiveness. For qualitative purposes, not all parameters involved need be considered because the goal might be to determine the direction or mechanics of a process or the origin of a feature. In fact, often the goal is to use the minimum number of variables. Quantitative models, however, must consider all important parameters because omission of a single significant variable will result in a wrong answer. Alternatively, if based on empirical relationships, these must be robust and have a quantifiable margin of error. Failure to recognize the difference between the two model types is at the heart of existing problems of calculating longshore transport.

Successful prediction must involve a sufficiently small error to make the prediction useful. Accuracy within say 10% of reality is likely to be needed for longshore-transport sand volumes used for coastal engineering purposes. This would not disrupt most cost/benefit ratios, beach lifespan estimates, and cost estimates. Longshore-transport calculations citing the probability of various outcomes would be useful, but most coastal engineering models are deterministic (they yield a single number), and a political and policy system has grown up around absolute longshore transport volumes (particularly net annual volumes) cited without error bars.

To borrow a concept from global climate modeling (Raynor 2000), mathematical modeling of longshore sand transport takes place in a *cascade of uncertainties* that involve the triple interaction of air, sea, and sediment. The *cascade of uncertainty* in predicting longshore transport (Fig. 2) begins with the imperfectly understood components that influence sediment movement (climate and oceanographic forcing; transport processes; feedback), and in the case of applied models proceeds through the vagaries of engineering practice and ends with the unpredictable behavior of humans who decide on coastal management policy and play politics with sand volumes.

Climate variability
Atmospheric processes
Oceanographic processes
Longshore transport processes
Nearshore morphology changes
Engineering practice
Policy
Politics

FIG. 2.—The cascade of uncertainties in the prediction of longshore sand transport for applied purposes.

FIELD MEASUREMENT OF LONGSHORE TRANSPORT

Attempts have been made to measure longshore sediment transport at a variety of temporal and spatial scales. Approaches used to determine instantaneous longshore transport volumes include sand traps, natural and artificial tracer grains, optical and acoustic techniques, and bedform observations (e.g., Komar and Inman 1970; Ciavola et al. 1998; Wang et al. 1998; Miller 1999). These approaches were reviewed by Dugdale (1990), Bodge and Kraus (1991), and White (1998), all of whom noted that near-bed and bedload transport remains difficult to measure in the surf zone. The major limitations of such measurements lie in (i) their inability to assess storm transport, (ii) their inability to simultaneously assess longshore sediment transport across the entire active profile, and (iii) the fact that the width of the active zone of transport changes temporally.

The combinations of factors that contribute to longshore transport are numerous such that field measurements under a given set of wave conditions also reflect, *inter alia*, current, wind, bedform, grain size, boundary-layer thickness, and sediment availability conditions (Fig. 1). This renders generalizations regarding longshore transport volumes difficult if not impossible. The development of beach cusps, for example, is a morphological response to either infragravity waves or self organization (Coco et al. 2000, 2001). Cusps inhibit longshore transport and yet cannot themselves yet be definitively understood in terms of formative processes. In this situation of incomplete knowledge of geomorphic processes in the littoral zone it is unreasonable to expect a realistic measure of longshore transport.

Setting aside the problems of direct measurement, the question of how to scale up longshore sand transport volumes determined in experiments of a few minutes, hours, or days to a number encompassing all transport that occurred in a year, presents huge uncertainty because of the multifarious combinations of process factors. It is made all the more difficult by the uncertainties associated with storm occurrence and the volume of transport during storms.

Measurement of changes in shoreline morphology provides a longer-term measure of sand movement including volume changes of tidal deltas, spits, downdrift barrier island growth, and shoreline retreat rates (Komar 1976). Measurement of volumes of sand annually removed from shipping channels or volumes of sand accumulated updrift of jetties and groins provides the same information (Wallace 1988). All these are measures of the volume of accumulation or removal but *not* the volume of transported sand, which can be vastly different. Accumulation rates and volumes can be very useful in understanding the dynamics of nearshore processes and interpreting geomorphic change, but actual transport rates are required for many engineering applications.

Measurement of sand transport in the wide and complex surf zone of important storms remains a missing link in field measurement of longshore transport (Wright 1995; Wright et al. 1987). Meaningful instrumentation of surf zones to simultaneously measure all the sand transport by waves, wind-driven currents, and eolian processes in offshore, onshore, and alongshore directions has not been achieved under fair-weather conditions, let alone storm conditions. Recent efforts to measure storm-related transport (Miller 1999) have highlighted the importance of storms and support the contention of Carter (1988) that on some low-wave-energy beaches storm-related processes may be the dominant mechanisms of sand transport. Further, Storlazzi and Field (2000) concluded that longshore transport between pocket beaches on an indented coast was driven by high-energy events, in contrast to linear shorelines, where lower energy events contributed to littoral transport.

In summary, for the reasons that longshore transport is temporally and spatially variable even at a single location, effective measurement is difficult and probably unattainable. "Since the waves break over a broad zone determined by the variation in wave height and the tidal range, no fixed instruments can measure these parameters" (Seymour and Higgins 1978). Certainly at present we have no dependable, verifiable, and consistent field measure of net or gross instantaneous or annual longshore transport volumes against which predictions can be compared.

Even if longshore transport could be measured at a single location for all conditions over a period of several months or years, each measure is only representative of the exact combination of conditions (forcing factors, sediment character, and topography) existing at that time and place.

THE THEORETICAL APPROACH

Given the difficulties involved in field measurement outlined above, theoretical and modeling approaches present an alternative to the field assessment of longshore drift. A number of models exist that seek to predict longshore sediment transport on the basis of knowledge of several controlling factors. Among the most important mathematical models used to determine longshore transport are the CERC equation (USACE 1984) and the model GENESIS (Hanson and Kraus 1989), LITPACK, from the Danish Hydraulic Institute, and UNIBEST, developed at Delft Hydraulics in the Netherlands. The shortcomings of the GENESIS model are well known (Young et al. 1995). The CERC equation and LITPACK, which represent probable end members in the spectrum of conceptual approaches to the prediction of longshore transport, will be emphasized in this report.

THE CERC EQUATION

The CERC equation (USACE 1984) is the most widely used approach to determine longshore transport sand volumes worldwide. This empirical equation (and a number of others that are closely related) is a simple energy-flux equation that assumes sand transport Q is proportional to the flux toward shore of alongshore momentum from breaking waves as follows

$$Q = k\frac{\rho H_b^2\sqrt{gd_b}}{16(\rho_s - \rho)a'}2\sin\alpha_b \qquad (1)$$

where k is a sediment transport coefficient, H is breaking wave height, d is the depth of water where the waves break, ρ_s is density of quartz sand, ρ is density of sea water, and α is the angle of wave approach to the shoreline.

Seymour and Higgins (1978) noted that "an estimate of gross transport by this method (CERC equation) might easily be in error by a factor of three or four." They further concluded that transforming waves from deep water using refraction theory might not provide sufficient accuracy to predict net transport. But this expression of concern early in the history of use of the CERC equation seems to have received little notice.

Implicit in the use of the CERC equation are several assumptions discussed in detail by Theiler et al. (2000). One of these is the value of the empirical coefficient known as the longshore transport coefficient (k). The all-important k was first determined on the basis of fourteen, 2–4 hour long, field tracer experiments by Komar (1969), who studied fair-weather longshore sand transport on two beaches, one in California on the Pacific Ocean and the other in Mexico along the Gulf of California. The calculated longshore transport volume was multiplied by 0.77 to equal the field-measured longshore sediment transport volume. The value 0.77 (Komar and Inman 1970) subsequently became the recommended sediment transport coefficient value in the Shore Protection Manual (USACE 1984). Komar (1976) concluded from the relationship between longshore wave power and immersed-weight transport from a variety of different types of beaches that beach slope and grain size were unimportant in longshore transport.

Komar (1998) subsequently revised this figure to 0.70 on the basis of additional published field data for sand of a wide range of mean grain sizes (0.15 to 1.0 mm) but acknowledged that selection of a k value produced uncertainties in calculations of longshore sediment transport rates from any formulation. In spite of studies that demonstrated the control of grain size on longshore sediment transport (Komar 1977), no account is taken of grain size in this formulation (Komar 1998).

The simplifications of the Komar and Inman formulation and its derivative, the CERC equation, clearly do not address all-important elements of longshore transport. Equally, there are severe limitations in the field measurements involved in its establishment. In development of the CERC equation and similar formulations, one unknown has been compared with another and "corrected" with a coefficient (k). Clearly there is no justification for use of such an approach. Countless determinations of longshore drift rates using this approach may be wrong.

The practical ramifications of this approach are that once a number for annual sand transport is calculated it can become a more or less permanent fixture (indeed, Komar 1976, p. 218 and 1998, p. 384) reproduces a table of longshore drift rates derived from Johnson (1956) as "littoral drift rates along coasts."

The Komar and Inman (1970) paper and its derivatives (including the CERC equation) not only seem to provide the basis for an *expected universe* for longshore transport sand volumes, they also seem to have set the standards for future unwavering and unquestioning belief in longshore-transport models. The paper has been immensely important and very damaging to coastal science.

LITPACK/MIKE MODELING SUITE

An alternative, more complex applied modeling approach is exemplified by the LITPACK/MIKE modeling suite of the Danish Hydraulic Institute. This approach appears to derive from the viewpoint that because each beach is different and beach processes are very complex, more parameters should be included in models.

LITPACK comprises several individual models that calculate longshore currents and littoral drift (LITDRIFT) sediment transport (STP), cross-shore profile evolution (LITPROF), and coastline evolution (LITLINE). This assemblage of models encompasses many more implicit and explicit variables or parameters than the CERC equation (28 versus 7; Table 1). Some of the additional parameters incorporated in LITPACK are very important controls of longshore sand transport. These include underlying geology of the shoreface, sea breezes, coastal currents, bottom roughness and bed forms, various wave theories and wave conditions, and offshore bars that are allowed to change shape and position with time. The user may select and input a value for these parameters but is faced with the difficulty of selecting an appropriate value for factors that are difficult to generalize or are not easily reduced to a single number. In addition, several factors, including for example, origin and evolution of offshore bars are poorly understood and no universally applicable model exists in the current literature that describes their behavior.

Diegaard et al. (1986) used wave records and sediment infilling of a human-made trench across the shoreline to test their model against field measurements. Depending on whether a uniform wave field or a Rayleigh wave distribution was assumed, the simulation sand volume varied between 0.6 and 1.2 of the drift volume measured in the trench.

TABLE 1.—*A subjective and qualitative classification of longshore transport parameters arranged in order of probable decreasing global importance. Asteriks designate parameters that are implicitly and explicitly considered by the CERC longshore transport equation. Parameters in boldface are among those considered in the LITPAK model.*

ALWAYS IMPORTANT
***wave height**
***angle of wave approach**
storms
***shoreface morphology**
morphologic feedback - bar shape changes
***grain size**
underlying geology
USUALLY IMPORTANT
offshore bar configuration
wave current interactions
***wave period**
wave setup
directional wave spreading
wave energy friction loss
cross shore transport by waves
cross shore transport by currents
coastal type
sediment supply
engineering structures
revetments
breakwaters
beach nourishment
beachrock
nearshore winds
lateral sorting-armoring-lags
bedforms
bottom roughness
SOMETIMES IMPORTANT
bed liquefaction
beach state
storm surges
tidal range
tidal currents
coastal currents
sea water infiltration
Wave conditions
***regular**
Irregular
Rayleigh
Battjes and Jannsen
wave theory
Stokes
Cnoidal
Vocoidal
Isobe and Horikawa
Doering and Bowen
***wave breaking parameters**
wave reflection
infragravity waves
wave reformation (after break)
Shield's parameter
beach state
water temperature
sediment sorting
beach stratigraphy-vertical sorting
clast shape
***grain specific gravity**
groundwater (pore pressure)
organic mats
aeolian loss or gain
overwash loss
gravity currents
turbidity currents
bioturbation
rip currents
storm surge ebb

Such results do not of course mean that the model will produce corresponding accuracy at any other site, or indeed the same site at a different time, because the heterogeneity in the field (in terms of dynamics, sediments, and topography) differs in time and space.

LITPACK is a black-box system devised by a group competing for business in coastal management. The LITPACK user cannot determine just how the model parameters are used, although Diegaard et al. (1986) supply some information for the longshore-drift model.

The difficulty of such an approach is that adding more incompletely understood variables simply increases the dilemma of uncertainty. With each added process or attribute comes the uncertainty of describing it and the uncertainty of its interaction and feedback with other variables. The modeler moves from the *sin of omission* to the *sin of commission.* Sins of omission occur in simplified models with too few parameters to adequately describe the process being modeled at a level of accuracy needed for engineering purposes, such as the CERC equation-type model. The LITPACK/MIKE type model is an example of the sin of commission.

MODEL IMPROVEMENTS

Of course, the coastal modeling community is engaged in the development of new model formulations, and it is believed by some that model refinement will lead to better prediction. For example, originally (USACE 1973, 1984), the coefficient k was assumed to be universally applicable on all beaches. The value 0.77 has been widely applied and continues to be applied to calculations of longshore transport on both US and European shorelines. This approach is an example of the *assumption of universal applicability of mathematical model parameters* of beaches. One model and one sediment-transport coefficient was assumed to fit all beaches.

Later, different values of k were recommended for different beaches or types of beaches (Wang et al. 1998). The value of k in actual use has occupied scientists and engineers for a long time (e.g., Allen 1981, 1985; Dean et al. 1982; Kraus et al. 1982; Kamphuis et al. 1986; Ciaviola et al. 1997). Widely varying (two orders of magnitude) k values, from 0.014 to 2.32, on different beaches have been recommended. Wright et al. 1987 argue that there are many k values for a single beach and indeed published values of k for beaches near Oregon Inlet, North Carolina have ranged from 0.2 to 1.0.

Recently k has been used as a multiple to achieve a target number for longshore-transport volumes determined in previous studies (USACE 2001), reducing it to a virtual fudge factor.

Another popular approach in model enhancement is to test a variety of models against each other. Such a test of LITPACK and other models was performed by Szmytkiewicz et al. (2000). They calibrated GENESIS, LITPACK, UNIBEST, and SAND94 (Polish Academy of Sciences) models using a transport rate determined by a one-year accumulation of sand behind a groin along the Baltic Sea. Validation and verification of LITPACK based on known shoreline changes resulted in correlation coefficients ranging from 0.43 to 0.70. The other models fell into the same range of accuracy. Szmytkiewicz et al. (2000) leave it to the reader to judge whether the models have produced numbers with sufficient accuracy for engineering purposes.

DISCUSSION

Several extant limitations in conceptual understanding and field measurements severely impair our understanding of longshore sediment transport. However, the widespread application of such models creates the erroneous impression that the process is sufficiently well understood to be modeled accurately. Even more serious is the way in which these applications impair future understanding by creating an expected universe of longshore drift volumes. We discuss these limitations below

Cognition and Complexity

Cognition refers to the level of understanding of individual model parameters involved in longshore transport of sand. The modeler must consider whether our state of understanding of each of the model components is sufficient to justify acceptance of the longshore-transport volume obtained in a model run (Fig. 1).

The interactions illustrated in the classical Krumbein diagram in Figure 1 and the parameters involved in those interactions are not well understood. For example, it is clear that the geology underlying the shoreface plays a role in longshore transport (Riggs et al. 1995; Schwab et al. 1999; Schwab et al. 2000). Underlying rock outcrops influence sediment supply and impact on the wave energy and angle of wave approach but our level of understanding is insufficient to permit quantification of the relationships. Longshore-transport models that take no account of sediment supply can at best be considered to predict potential transport rates (Resio 1978). Because no method has been established to account for sediment availability in longshore-transport models, this is an obvious limitation of predictions. Most important perhaps is our lack of understanding of longshore transport in storms.

The quality of the characterization of individual parameters is also part of the cognition problem. The following considerations illustrate the problem related to choice of values for wave height and grain size by model users.

Wave height

- What height to choose?
- How to account for storm waves?
- How to account for multidirectional wave trains?
- What wave theory to use (Stokes, Cnoidal, etc.)?
- How to describe the wave spectra?

Grain size

- Which measure of central tendency to use?
- Which measure to use for sorting?
- How to characterize the size of beach sediment with a wide range of grain sizes (a common situation)?
- How to account for the impact of grain shape (e.g., platy shell fragments) on sediment transport?
- How to account for changing grain size (e.g., formation of storm lags) during important beach "events"

There are many definitions of *complexity.* According to Perrow (1999) a complex system is one in which interactions occur in unexpected sequence. Sherden (1998) notes that a complex system exhibits periods of order and predictability punctuated (unpredictably) by unexpected moments of self-generated turmoil. By these simple partial definitions, the longshore sand-transport system (and earth surface processes in general) is a complex system. The large number of parameters (Table 1) that interact with one another in nonlinear fashion virtually assures this. The factors that run this system may kick in at various times, intensities, durations and directions.

The parameters that control beach behavior vary in importance in time and space. A scenario of major importance to sand transport can be devised and undoubtedly exists at some location or time for many (perhaps 70) parameters. For example, sediment sorting may be important when shell or gravel lags form and hinder sand transport (Carter 1976), but in well-sorted beach sand such lags will not form. The impact of local winds is not considered in most models but Ciavola et al. 1997 observed a sixfold increase in sand transport when locally brisk winds blew in the same direction as longshore currents. Masselink and Pattiaratchi (1998) noted a hundredfold increase in suspended sediment transport rate and important changes in beach morphology due to sea breezes. Bottom currents are poorly understood, as is geologic control of shorefaces.

A recent side-scan sonar mosaic off Wrightsville Beach (Fig. 3), a barrier island in North Carolina illustrates several poorly understood factors that affect longshore transport. The light gray areas in the southwest one-third of the mosaic are rock outcrops which affect wave direction and height as well as on onshore and offshore sediment transport and sediment supply that will contribute to longshore transport. The elongate, narrow, light colored (coarse shell hash) strips are linear rippled depressions and are bedforms believed to be formed by laterally flowing currents. These linear depressions may also channel sediment seaward during storms. None of

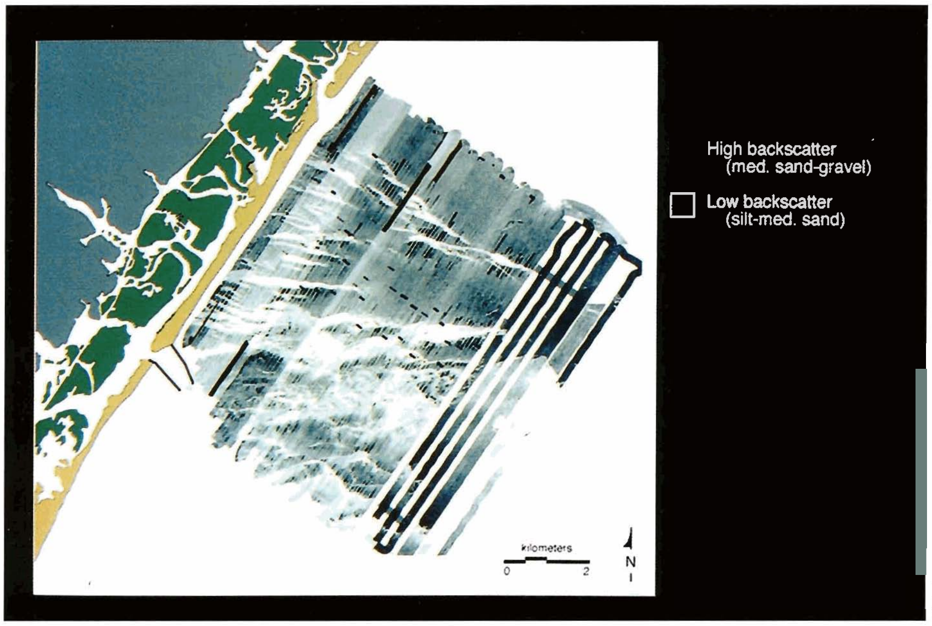

FIG. 3.—A sidescan sonar mosaic of the shoreface and inner continental shelf off Wrightsville Beach, North Carolina, a barrier island. The image illustrates a number of poorly understood factors (see text) that affect longshore transport. The shoreface is not a smooth surface of uniform grain size as assumed by the standard longshore transport models. Image furnished by Rob Thieler and the U.S. Geological Survey.

these processes and features are considered in the models used to predict longshore transport. It is conceivable that the parameters that control beach behavior may be better understood in the future and thus solve or reduce the *cognition problem.*

The long list of parameters (Table 1) speak to the *complexity problem.* It is highly unlikely that we will ever solve the complexity problem and correctly predict, at societally useful time and space scales (decimeters over decades), the interaction of the many factors that operate simultaneously on multifarious beaches to control longshore transport. Thus we contend that the quantitative modeling approach in developing new formulations and applying new models of increased complexity is pointless.

The underlying premise, that we can quantify longshore transport at anything other than a site-, time- and condition-specific manner, is wrong. Because we cannot understand the interactions between dynamic forcing factors (sea breeze and wave-current interaction), and there is an infinite combination of processes and sediment characteristics, it is inconceivable that current approaches will ever quantify longshore drift at the accuracies demanded by engineering applications. Field heterogeneity is too complex. Our best expectation is to develop better understanding of the relative importance of various factors and groups of factors in longshore transport and to use this enhanced understanding to provide qualitative statements on longshore transport.

The Political Parameter

Because of the societal context in which coastal engineering takes place, politics strongly affect longshore sand transport volumes. Given the flexibility of models to produce various results (by selection of various k values in the CERC-type approach, and alteration of input variables in the more complex LITPACK-type models) that cannot be verified by field measurement, consultants are able to calculate longshore-transport volumes to suit their clients' needs. Equally, government agencies have the capacity to determine volumes that promote agency objectives. Given the extent of human activity at the coast, and the consequent high level of coastal engineering activity, this is a widespread problem. Therefore in order to determine the credibility of any sand-volume number, one must know its political context.

Political sand volumes may simply represent an "optimistic" interpretation of the model. Optimistic science is hardly unknown in geology. Petroleum geologists are encouraged to present the optimistic view of oil prospects to management. In beach science, model parameters (which are often poorly understood anyway), can be altered to produce a "better" sand volume. Very small alterations in such parameters as wave height and wave direction can make large differences in calculated transported sand volumes. Kumar et al. (2001) observed that errors as small as 0.5 degrees in wave orientation relative to the shoreline could change both direction and the volume of sand transport. In the absence of techniques for field verification as outlined above, there is great scope for tinkering with coefficients and with different input parameters to achieve the desired volume. The choice of wave parameterization as discussed above for the LITPACK model verification provided results between 0.6 and 1.2 of a supposed reality and indicates the ease with which a desired result can be achieved. Many additional factors could be modified in order to provide different results, all of which are, from the model perspective, equally valid. The following two real-world U.S. examples illustrate common political contexts.

The net longshore-transport volume predicted for a proposed nourished beach in Nags Head, North Carolina (Boss et al. 1999) was unacceptably large leading to an unacceptably high project cost. This was because the volume of sand that would flow downdrift (south) to Oregon Inlet would add costly navigation channel maintenance to the project's cost (USACE 2000). The wave approach angle was changed by 5 degrees, the model was re-run, and the volume of sand predicted to move into the navigation channel was much reduced.

On east–west trending Bogue Banks, a North Carolina barrier island, the initial estimate of longshore transport was a negligible 10,000 cubic yards (ca. 7,650 cubic meters) per year to the east (Langfelder et al. 1970). A recent revised estimate by the U.S. Army Corps of Engineers, released via the media, was 1 million cubic yards (ca. 765,000 cubic meters) per year to the west. Geo-indicators such as downdrift inlet stability and longshore current directional indicators suggest very small sediment transport rates. If sand transport was a million cubic yards per year, however, this would enable sand trapping in the Beaufort Inlet dredged navigation channel at the east end of the island to be blamed for the island's critical beach erosion problem. If dredging activities could be shown to be responsible for the erosion problem, funding to the agency would be more readily available for a beach nourishment project.

THE EXPECTED UNIVERSE

The major problem with calculations of longshore transport is that the process is entrapped in an *expected universe* within which practice is far removed from scientific understanding. The entrapment has limited our horizons, obstructed objectivity, and provided unwarranted confidence in our numbers (which fall within prescribed correct boundaries) in spite of the huge uncertainties involved in their derivation.

Expected universes in mathematical modeling are not unique to the study of longshore transport. Raynor (2000) gives two examples in modeling of global climate change. Heat exchange between the ocean and the atmosphere is a very sensitive model parameter, which has led some modelers to impose a "flux adjustment." Raynor describes this as a "guesstimate" and "a clear example of how expert judgment may play an important role in the modeling process" that is invisible to policy makers. A second institutional factor that also exemplifies the *expected universe* of global climate change modeling is the anticipated change in global temperatures due to a doubling of atmospheric carbon dioxide. The range, 1.5 to 4.5 deg C, is not model derived but is "the result of diffuse expert judgment and negotiation among climate modelers" (Raynor 2000).

Groundwater flow at the proposed Yucca Mountain, Nevada nuclear waste repository provides another example of an expected universe. Between 1988 and 1996 the percolation flux through the welded tuff overlying the proposed repository tunnel was assumed to be of the order of 0.1 mm per year. To accept that very slow flow of water, it was also necessary to assume that ground water traveled through pore spaces and not fractures. The 1996 discovery in tunnel ground water, of "atomic bomb" chlorine, derived from adjacent bomb test sites, precipitated a revision of the estimate, upped the assumed flow rate of ground water by an order of magnitude, and demolished the expected universe; clearly fractures were involved.

In the eight years during which the low number for percolation flux governed and constituted the *expected universe,* all modeling of ground water flow and all designs of the repository assumed that the number was correct, in spite of widespread understanding that the flux rate was a tenuous assumption at best. Metlay (2000) suggests that it was a form of institutional behavior that favored support of the optimistic lower number and resisted going in the "pessimistic" direction.

The *expected universe* of longshore-transport numbers has close similarities to the universe of Yucca Mountain. The sand-volume numbers are based on assumptions as absurd as the Yucca Mountain belief that ground water did not flow through fractures. When the revelation of more-rapid-than-expected ground-water flow came at Yucca Mountain, major changes in the approach to nuclear repository design were required. Recognition of the questionable basis of beach engineering will also require considerable rethinking.

Much research on longshore transport is running on principles of beach behavior that are three to four decades old. The concept of the shoreface profile of equilibrium (Bruun 1954, 1962; Dean 1991), the basis of most US beach models, is a startling example of preservation of the *expected universe.* Grain size is assumed to determine shoreface shape, but no such simple relationship between shape and grain size exists (Theiler et al. 2000). Other factors, including wave energy, sediment supply and underlying geology are known to play a role in governing shape but use of the grain size assumption continues unimpaired. Probably most estimates of longshore transport on major beach nourishment projects assume an equation-determined beach profile rather than use the more complex and variable natural profiles (e.g., USACE 2000, 2001).

The system works to preserve the *expected universe* and to defend it from the onslaught of nonbelievers. Novel findings regarding longshore drift processes (e.g., Brocchini 1997) are weakened by comparison with previous results to assure their fit in the expected universe. The culture of beach-behavior modeling opposes change, as do most cultures. An accelerating tide of criticism of beach model assumptions (Kraft et al. 1987; Pilkey et al. 1993; Carter and Woodroffe 1994; Wright 1995; Haff 1996; Thieler et al. 2000) remains unanswered. Nor have criticisms of the mechanics of beach behavior models (Konikowe and Bredehoeft 1992; Oreskes et al. 1994; Young et al. 1995) jarred the establishment in any fundamental way. A leading coastal-sedimentation textbook (Komar 1998) discusses models but does not acknowledge model criticism.

Assurances of recognition of flaws and uncertainties in model applications are commonplace in the literature. For example, Young et al. (1993) list a number of serious model uncertainties mentioned in the technical manual for the GENESIS model (Hanson and Kraus 1989). That the uncertainties are not analyzed in any fashion and are ignored in actual applications appears to indicate that no one wants to leave the universe.

In actual application, deterministic model runs of beach sand transport produce solid numbers. When numbers reach politicians, policy makers, and other users, they are unencumbered by any mention of uncertainties. In the context of global-change models, Raynor (2000) notes that "careful caveats about the scope and purpose of models tend to melt into the background when both practitioners and users confront the apparent but misplaced concreteness of tables and graphs representing various model runs."

It is beyond the scope of this paper to explore the complex problem of freeing ourselves from the expected universe. It could happen in applied modeling immediately if political entities would no longer require precise predictions (such as the cost-benefit ratio required in U.S. projects) and cost estimates for aspects of beach engineering projects. Quantitative modeling of longshore transport would, however, remain ensnared.

Unfortunately there is no atomic-bomb chlorine discovery on the horizon that will jerk society back to reality on the shoreline. The problems with the modeling approach to determining longshore transport are already as apparent as the problem of ignoring fractures in ground-water dispersal was at Yucca Mountain. Yet getting out of the *expected universe* will be difficult.

We believe that a fundamental reassessment of longshore drift is required. This does not mean a modification of model parameters, development of increasingly complex models, or development of new empirical relationships, but a complete reappraisal of how we view longshore drift. Insufficient understanding of the process has been masked by the widespread use of apparently sophisticated models that give the impression of a good understanding of the processes of transport. We conclude that our present understanding permits only a qualitative estimate of direction of longshore drift and identification of some of the controls. The use of existing *quantitative* models of longshore drift should be discontinued—they have no basis in conception or reality—and instead effort should be focused on the study of processes of longshore transport at a variety of spatial and temporal scales and under a variety of conditions for different types of coastal systems.

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