Longshore Transport Volumes: A Critical View

Authors: Pilkey, Orrin H., and Cooper, J. Andrew G.

Source: Journal of Coastal Research, 36(sp1) : 572-580

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.572

Journal of Coastal Research	SI 36	572-580	(ICS 2002 Proceedings)	Northern Ireland	ISSN 0749-0208

Longshore Transport Volumes: A Critical View

Orrin H. Pilkey† and J. Andrew G. Cooper‡

†Division of Earth and Ocean Sciences
Nicholas School of the Environment
Duke University, Durham, NC 27708
USA

‡Coastal Studies Research Group
School of Biological and Environmental Sciences
University of Ulster
Coleraine BT52 1SA
Northern Ireland, UK

ABSTRACT

The methods used to determine or predict volumes of sand transported by longshore currents are briefly reviewed. We argue that the methods are flawed and that a fundamental re-examination of both field and theoretical approaches is in order. Net transport numbers obtained by any existing method should be considered order-of-magnitude values at best that are in no case sufficiently precise for coastal engineering purposes such as prediction of beach nourishment costs and environmental impacts.

ADDITIONALINDEXWORDS: *sediment transport, GENESIS, LITPACK, CERC equation, coastal processes, mathematical modeling.*

INTRODUCTION

The amount of sand in transport along beaches is a critical environmental measure for both basic and applied coastal studies. For example, understanding coastal and barrier island evolution requires at least a qualitative sense of beach sand transport and accurate sand volumes are a critical component of the design of shoreline armoring and beach nourishment schemes. Such volumes, commonly expressed as sand volume per year, are an indispensable part of determining the environmental impact of structures and beach nourishment as well as predicting the long term costs of all kinds of coastal engineering.

Longshore transport volumes are determined both by modeling and by direct measurements in the field. In this paper we argue that scientists and engineers do not do a good job by either approach. Both the models and field measurements have major limitations and there is no independent measure of the accuracy of either. Physical models (wave tanks) offer little help in this regard. At best, estimates might be the right order of magnitude and at least could be far from reality.

We believe coastal scientists and engineers have created a mindset within which estimates of annual net longshore transport are made. This mindset restricts our thinking and fosters our acceptance of longshore sand transport volumes as the gospel truth in spite of the huge uncertainties involved. Coefficients have even devised that are used to bring peculiar abnormal or unsatisfactory transport volumes back within the confines of this mindset. A fundamental re-examination of the approach to the longshore transport volumes issue is in order.

THE FIELD APPROACH

On natural shorelines, not impacted by humans, field evidence or geo-indicators pointing to the volume of longshore transport are not particularly abundant. The width of a beach and dune system, while indicative of the volume of sand in the system, does not necessarily reflect the annual volume of sand that is moved past the beach. Whether a beach is wide and dissipative or narrow and reflective is not likely to be a function of longshore transport volumes either. In barrier island systems however, the rapidity of migration of inlets may reflect the direction and volume of net longshore transport as may the rate of elongation of a spit. Such changes can be misleading as several studies have documented inlet migration and spit elongation against longshore drift (REDDERING, 1983). In addition the rate of sand loss along an eroding shoreline reach can provide a minimum volume of annual longshore sand transport.

Broadly speaking, there are three methods of determining longshore transport volumes in the field. These are: (1) tracers; (2) direct measurement of moving sand; and (3) measurement of morphologic changes over time. WHITE (1998) reviews the state of the art of measurement techniques for beach sand transport that fall into the first 2 categories. Tracers commonly are fluorescent sand grains that are released in the surf zone to be later partially recovered, scattered in a downdrift direction. Sand traps are intended to capture (or measure in some way including optical and sonar methods) sand moving in the surf zone. Morphological change records net loss or gain of sand from a nearshore system over a given time frame. In this method of longshore drift estimation, changes in such features as tidal deltas and shorefaces are assumed to reflect longshore transport quantities. This in itself may not be straightforward and a number of studies (e.g. REDDERING, 1983) have recorded spit growth and inlet migration against littoral drift. Related approaches involve measurement of volumes of sand annually removed from shipping channels or volumes of sand accumulated updrift of jetties and groins (WALLACE, 1988).

Each method has problems (BODGE and KRAUS, 1991) and it remains an unknown as to how close such numbers are to reality, especially when short term measurements are extrapolated to provide a net annual volume. For example, measurement of sand volume behind engineering structures is a measure of accumulation and not necessarily transportation rates. The two can be vastly different.

Perhaps the greatest weakness in field measures (and in the theoretical approach as well) is the inability to meaningfully measure storm-related transport. To our knowledge, no one has successfully carried out tracer or sand trap measurements during a significant storm. The studies of MILLER (2001) at the USACE pier in North Carolina are a significant step forward in the direction of storm-related sand transport measurement but the results are far from suitable for application to other beach studies. Morphologic changes during storms may involve large volume transport completely out of the system in an offshore, onshore or lagoonal direction. Sand accumulating in navigation channels may be partially or totally dispersed by storm surge ebb.

And then there is a fundamental question as to what constitutes longshore transport. Most trap and tracer studies are carried out in the swash zone and inner surf zone. Indications are that considerable sand transport occurs just beyond the surf zone on the shoreface. Recent studies of shoreface morphology (SCHWAB *et al.*, 2000) have revealed extensive systems of rippled linear depressions that are interpreted as large bedforms formed by laterally flowing currents. How much sand is moved parallel to the shoreline just beyond the surf zone is unknown. Is this sand part of the beach system? During storms, the entire shoreface may be within the surf zone as the depth of wave penetration increases. Also implicit in the mindset of those who apply longshore transport volumes is that annual net volumes of sand vary little from year to year.

Most of the longshore transport numbers that are actually used in engineering design are derived from mathematical models. Short term field measurements of the type just outlined are often used as backups to the equations, intended to assure that the model numbers are of the right magnitude. But is this a case of the blind leading the blind? Could it be that we don't know how much sand is transported on beaches?

In summary, the authors believe that there are few, if any, meaningful direct field measurements of total (net or gross) longshore transport volumes of sand on beaches. The complete sand movement/accumulation system (the complete sand budget) is never known. In addition, the longshore transport system is ill-defined and it is not clear in some cases what should be included as longshore transported sand. How to aggregate up, surf zone sand volumes determined in experiments of a few minutes, hours or days to a number encompassing all transport that occurred in a year, remains a huge uncertainty. The most important shortcoming, however, is our poor understanding of lateral sand transport on beaches during storms.

THE THEORETICALAPPROACH

In this discussion of models and equations used to predict beach behavior and particularly longshore transport, the mathematical details will be handled lightly. The interested reader is referred to a voluminous engineering and coastal science literature on prediction of beach behavior. In discussion of individual models we will emphasize principally the variables that are used to determine longshore transport sand volumes rather than the specifics of model machinations.

The process of determining net longshore transport volume by equations usually involves some combination or variation on the following five step process (PILKEY, 2000)

- **Obtain the deep water wave height** from wave gages or from hindcasting waves based on weather records.
- **Bring the waves across the shoreface** from deep water using a wave refraction model, assuming shoreface bathymetry is well known. One wave train is chosen if more than one exists.
- **Choose a wave height** in shallow water. Most models assume that most sand is transported by higher than average waves.
- **Break the waves** first choosing a shape of the surf zone sea floor. In US applications, most often this is the upper part of a mathematically determined shoreface (DEAN, 1991) assumed to be a profile of equilibrium.
- **Move sand.** It is usually assumed that sand is of uniform grain size and sorting and that none is lost to dunes, overwash or offshore.

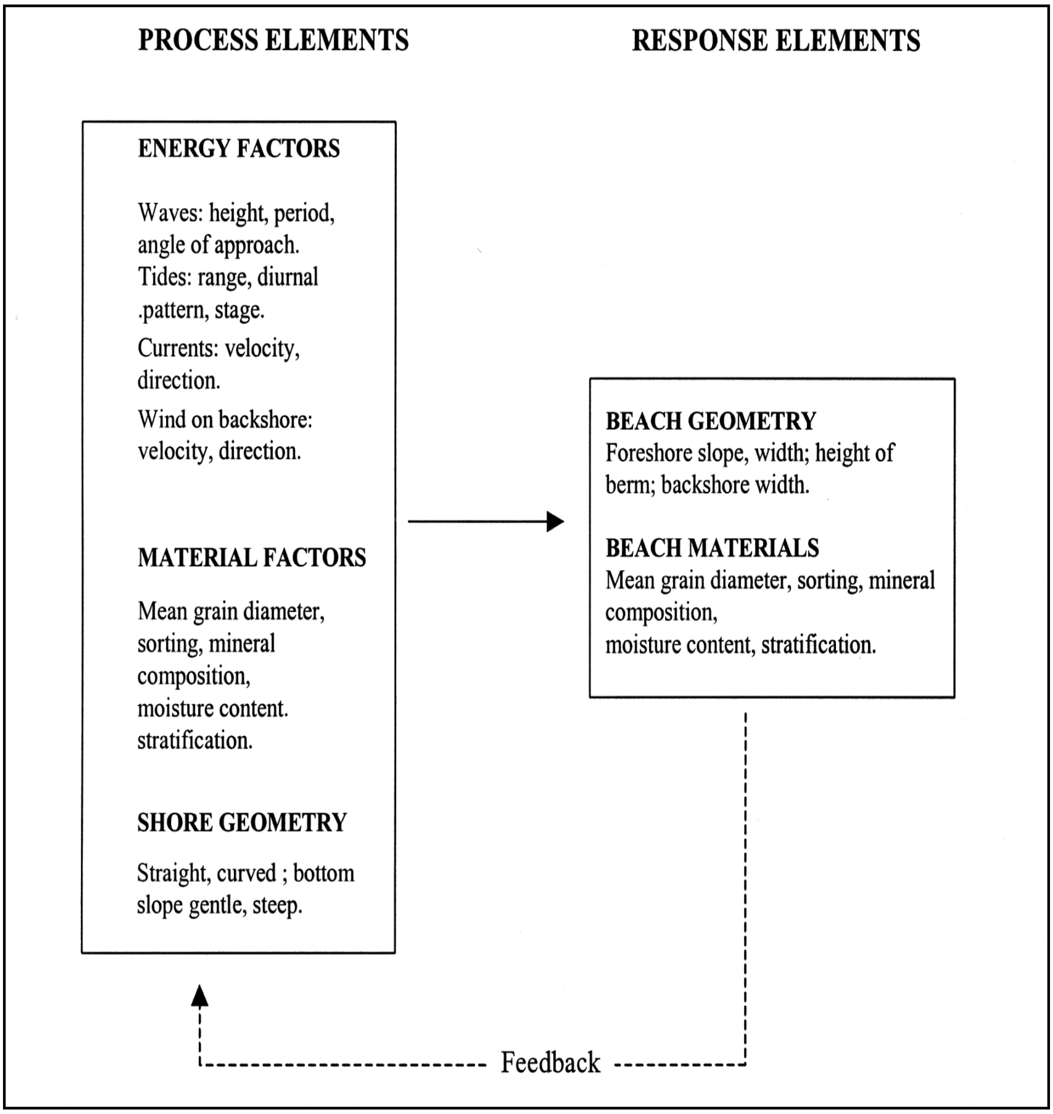

Figure 1. Conceptual process-response beach model (after KRUMBEIN, 1963).

THE MODEL PARAMETERS–WHAT MAKES BEACH SAND MOVE?

Nearshore processes include forcing factors and morphological responses and importantly, feedback between the two. This was recognized long ago by KRUMBEIN (1963) as shown in Figure 1.

A suggested qualitative hierarchy of relative importance of the various longshore transport parameters is shown below (Table 1). This is a purely subjective categorization intended mainly to point out the complexity of longshore transport of sand. Complexity is the principal reason why we think that this system cannot be reasonably modelled even close to the precision needed for engineering purposes. A larger number of beach behavior model parameters is given by THIELER *et al*. (2000).

Table 1. Beach behavior model parameters.

Systems	
	wave height
	wave angle
	storms
	morphologic feedback
	shoreface morphology
	underlying geology
Subsystems	
	offshore bar configuration
	wave current interactions
	coastal type
	grain size
	sediment supply
	engineering structures
	beachrock
	nearshore winds
Components	
	external factors (wind)
	bed liquefaction
	bed forms
	bed roughness
	beach state
	bottom currents
	storm surge
	tide range
	tidal currents
	coastal currents
Factors	
	water temperature (density)
	sediment sorting (lags - armoring)
	hydraulic conductivity
	groundwater (pore pressure)
	organic mats
	aeolian loss or gain
	overwash loss
gravity currents	
infragravity waves	
storm surge ebb currents	

Each of these parameters impact or at least can impact on the volume of longshore transport. The categories chosen (system, subsystem, components and factors) reflect a subjective and qualitative classification of beach behavior parameters arranged in order of probable decreasing global importance. For example, wave height and angle of approach are of primary importance but sand loss from the beach through overwash or temperature-related suspended sediment carrying capacities are of more local importance. Shape of the shoreface is fundamental to sand transport but sediment sorting is not, except perhaps in restricted circumstances when coarsest materials can armor the beach. Hydraulic conductivity is of little consequence on a well sorted sand beach but may be the most critical factor determining sand transport on a mixed beach with a significant gravel content (MASON and COATES, 2001).

The parameters at all levels will vary hugely in importance in time and space. A scenario of major importance to sand transport can be devised and undoubtedly actually exists somewhere, for each of the parameters on the list, even in the factors category. For example, underlying geology of a rocky beach with little sand will play a primary role in beach behavior and sand transport. But no rock, no role. Sediment sorting may be important when shell or gravel lags form and hinder sand transport, but in a well sorted beach sand, such lags will not form.

Excellent examples of the importance of minor parameters that are not considered in most US longshore transport models is furnished by the studies of CIAVOLA *et al*. (1997) and MASSELINK and PATTIARATCHI (1997). In the latter paper, sea breeze on Western Australian beaches was observed to increase longshore suspended sediment transport by a factor of 100. In the former study a six fold increase in longshore sand transport on a Portuguese beach occurred when locally brisk winds blew in the same direction as the longshore currents. This in spite of the fact that wave height and angle of approach remained identical to a previous tidal cycle when much less sand was moved. The impact of winds is not considered in most models.

The importance of this list of parameters is that it illustrates two important truths that apply to the mathematical modeling of any aspect of beach behavior.

1. **All beaches are different**. This may seem rather obvious but most models fall into the "one model fits all" category and the search for the universal model continues unabated (HANSON *et al*., 1999). According to the CERC equation, discussed below, the only important differences in longshore transport controls between beaches in different parts of the world are wave height, angle of wave approach, grain size and shape of the shoreface. Clearly this is a poor assumption as illustrated by the parameter list. Successful prediction of beach behavior would require that each reach of shoreline reach be treated separately and that the locally differing importance of many variables and their interrelationships be understood and taken into account.

2. **Beaches are highly complex systems**. This is clear from the list of parameters alone. The number of variables including the random occurrence of all-important storms and the mostly unknown nature of the relationships between the variable makes the complexity extreme.

Aside from the problem of missing and complex model parameters is the problem of data quality. In selecting a basic input parameter, the operator faces several critical questions. Take the system-level parameter ‘wave height’ for example.

- 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?

If it is accepted that all beaches are different and that important processes are omitted in the simulation of longshore transport it might seem reasonable from a modeling perspective to take this into account and simply add more parameters to the models? The answer to that one is that an already complex situation is made more complex. There are major questions about the validity of characterization of the few variables that are now considered in modeling. Adding more in the light of current uncertainties regarding processes and morphological feedback would simply increase the uncertainty and inaccuracy of the results. In addition the general assumption of a linear relationship between variables becomes a virtual tangle of assumptions as the number of variables increases. The modeler in this highly complex system would move from the ‘sin of omission’to the ‘sin of commission’(Figure 2).

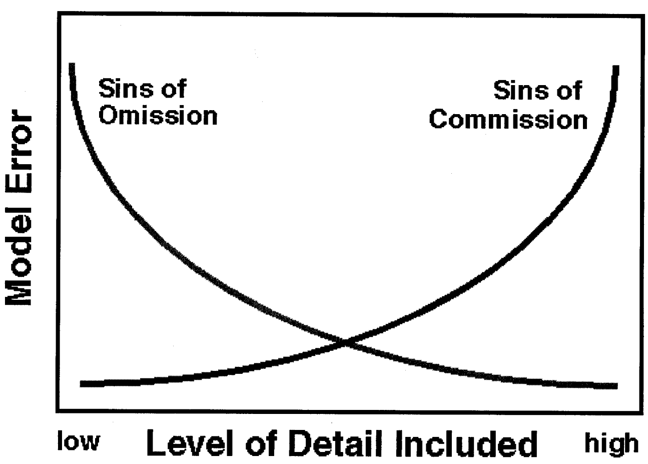

Figure 2. Diagram showing the relationship between model error and level of detail included (for discussion see text)

Sins of omission occur in simplified models with too few parameters to adequately describe the process being modeled. Perhaps the most widely used longshore transport equation, at least until recently, is the CERC equation (USACE, 1984). An example of the sin of omission, the CERC equation is a simple one that considers only wave height, wave angle and water depth to determine the wave energy flux. Longshore sediment transport, both suspended and bedload, is assumed to be proportional to the energy flux.

Sins of commission occur in models that attempt to use a large number of variables. This happens because as models are tested and inadequacies noted, the tendency is to "repair" or "improve" the model by the addition of more parameters. Of course with each added process or parameter comes the increased uncertainty of describing them. A good example of models in this category is a suite of coastal models called LITPAK/MIKE from the Danish Hydraulic Institute. LITPACK comprises several individual models that predict longshore currents and littoral drift (LITDRIF), sediment transport (STP), cross shore profile evolution (LITPROF) and coastline evolution (LITLINE)

THE MODELS

The CERC equation and k-The Root of All Evil?

The CERC equation used to calculate longshore sediment transport (USACE, 1984) relates the total sediment load, both suspended and bed load, to the flux of longshore energy of breaking waves in the surf zone:

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

Is one form of the equation where k is the sediment transport coefficient, H is breaking wave height, d is the depth of water where the waves break, p is density of quartz sand, p is density of sea water, a is density of the sediment and a is the angle of wave approach to the shoreline.

We believe that the mental model on which expectations of longshore drift volumes are based was established by KOMAR and INMAN (1970). On the basis of 4-hour field tracer experiments, KOMAR (1969) determined the sand transport on two U.S. beaches, one in California on the Pacific Coast and the other in Mexico along the Gulf of California. Simultaneously they determined the longshore transport using equations not much different in principle than the CERC equation. The measured longshore transport did not correspond to that determined theoretically. The field measurements were assumed to be correct so the model value was multiplied by 0.77 to bring it in line with the measured volume (KOMAR and INMAN, 1970). The value 0.77 then became the recommended k (designated the dimensionless sediment transport coefficient) value in the Shore Protection Manual (USACE 1984) for use with the CERC equation on any beach in the world. A number of important, but seldom considered, questions arise from this situation viz:

- What if KOMAR and INMAN'S (1970) field measurements were inaccurate? In that case, the 0.77 multiplier to bring the theoretical and field volumes in line, is also wrong. In that likely case, given the complexity of measuring longshore transport outlined above, all future model runs of the calibrated model using k would also be flawed.
- What if KOMAR and INMAN'S (1970) equation produced an incorrect volume of longshore sand transport? In that case, the 0.77 multiplier to bring the wrong theoretical and measured field volumes in line is again wrong. and hundreds of longshore transport calculations around the US and elsewhere are wrong.
- What if both the field and model derived answers are wrong? Why should this k produced in a few hours of experiment on fairweather beaches be a constant for either these beaches, or for all beaches under all possible conditions?

Not surprisingly, experience has shown that as in the pioneering work of KOMAR and INMAN (1970), field and theoretical longshore volumes almost always fail to coincide. ALLEN (1985) and CIAVOLA *et al*. (1997) both compared longshore transport (in New Jersey and southern Portugal, respectively) determined by equations and by tracer experiments and found that, in these cases, the models underestimated observed sand transport volumes by an order of magnitude.

In order to apply a sediment transport coefficient (k) to sand transport measurements the following assumptions made by KOMAR and INMAN (1970) continue to be made by contemporary investigators:

1. The sand volumes determined by field study are correct;
2. The sand volume determined by the CERC equation is incorrect but can be corrected with a constant k;
3. The coefficient k is applicable under any and all wave conditions on all beaches to "correct" the CERC equation.

These assumptions were not defended in the KOMAR and INMAN (1970) paper and we can discern no reason to accept them, especially not in the context of our much advanced understanding of nearshore processes in the new millennium. The KOMAR and INMAN (1970) paper not only seems to provide the basis for the mental model for longshore transport equations it also seems to have set the standards for future unwavering and unquestioning belief in beach behavior models. The paper has been immensely important and very damaging to coastal science and engineering.

The value 0.77 has been widely applied to longshore transport calculations using the CERC equation on US shorelines, including both Atlantic and Gulf of Mexico beaches in Florida. Later workers have noted widely varying k values, from 0.014 to 2.32 on different beaches.

The k problem has occupied scientists and engineers for a long time e.g. CAVIOLA *et al*. (1997), ALLEN (1985, 1988), DEAN *et al*. (1982), KRAUS *et al*. (1982) and KAMPHUIS *et al.* (1985). WRIGHT *et al.* (1987) argue that there are many possible k values for a single beach and indeed values of k for beaches near Oregon Inlet, NC have ranged from 0.2 to 1.0. making the use of the coefficient highly questionable. With the exception of WRIGHT *et al*. (1987) none of the workers concerned with the mathematical determination of longshore transport volumes have revisited the KOMAR and INMAN (1970) study to evaluate and question the assumptions behind the use of k.

The extent to which k is ingrained into our calculations of longshore transport volumes is illustrated by the recent study of WANG *et al*. (1998). These workers used cross-profile sand traps placed at a number of southern US Atlantic and Gulf surf zones. On the basis of 3 to 5 minute measurements they calculated k for a number of beaches, averaged the numbers and concluded that k = 0.08 for low energy beaches. The conclusion means that 3 to 5 minute observations were effectively scaled up to decades.

The widely used model GENESIS (HANSEN, 1989) uses two k values to calculate longshore transport as part of the model run. In a recent US Army Corps of Engineers design manual for a nourishment project on the North Carolina Outer Banks the k's are described as "calibration parameters .....assigned to achieve optimum model calibration". In this case, the k's were chosen to come up with reasonable longshore transport volumes based on longshore transport volumes calculated by earlier studies. It is a thought process (a mental model) that is compounded on many US shores, the practical ramifications of which is that once a sand transport number is calculated it becomes a more or less permanent fixture.

Danish black boxes -LITPACK

This is an assemblage of models that consider many more variables or parameters than the CERC equation. By one count, the CERC equation implicitly and explicitly involves 7 parameters compared to 27 for LITPACK. Some of the additional parameters incorporated in LITPACK are very important controls of longshore sand transport. These include underlying geology of the shoreface, wind, 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.

It might be assumed that the LITPAK model comes much closer to reality as measured by the number and critical importance of geologic and oceanographic parameters included. But including additional model parameters does not help unless they are well understood, not only in isolation but also in terms of their interaction with other parameters.

LITPAK is a black box system devised by a group competing for business in coastal management. The US Army Corps of Engineers (USACE) models (The CERC equation, GENESIS, SBEACH) were produced by a government agency, not involved in the commerce of consulting. In the US, such agencies are required to place all their studies in the public domain. As a consequence, the USACE models are explained in detail in manuals that are free for the asking. It is a system that makes model evaluation and criticism relatively simple.

The LITPAK-user, on the other hand, cannot determine just how the model parameters are used although DEIGAARD *et al*. (1986) supply some information for the longshore drift model. For example, one model option allows the shape of the offshore bars to change with time in response to ongoing oceanographic conditions but offshore bar origin and evolution is poorly understood. Unless these workers have performed an unheralded breakthrough in the understanding of offshore bar genesis, the operational basis of the model is questionable.

The same lack of understanding exists for all the other parameters in LITPACK: i.e. how to characterize the waves, currents and seafloor character in this highly complex and only partly understood system responsible for moving sand in the littoral zone.

THE POLITICS OF LONGSHORE TRANSPORT

It is important to address the politics of the use of the theoretical approach to the determination of longshore transport volumes. Many coastal scientists would prefer to let coastal managers and others worry about this but in actual practice the sand volume numbers are determined in a heavily political context. Agencies, consultants and companies that determine longshore transport volumes are rarely in a purely academic environment. Often modelers are under pressure to find a number on the low side or perhaps on the high side depending on their client’s needs - and it is a simple thing to manipulate numbers in models filled with huge uncertainties.

The volume of sand moving alongshore is a number on which multi-million dollar projects can rise or fall. It should therefore not be surprising that it can be a politicized number which in turn can polticize the models. For example, if longshore transport is too large a nourished beach, may fail to meet required standards of durability. In the case of federally funded US nourished beaches, the cost benefit ratio must be favorable and this may depend on the rate at which the beach will disappear due to longshore transport.

We have observed in numerous exchanges and discussions between beach designers, journalists, environmentalists and politicians that the models are "sold" as the sophisticated, state-of-the-art approach to coastal engineering. Perhaps this is so, but they are nonetheless flawed. Since few of the citizenry and even many coastal scientists cannot evaluate the models, in practice they are opaque to criticism. This, combined with the "state of the art" legend, makes models a very powerful political tool to support or oppose coastal engineering projects.

Following are some US examples of misuse of models without names and agencies included, to protect the innocent.

Change input data to get a "better" answer - Initial calculations of longshore transport rate from a proposed nourished beach were judged to be too large because too much sand would flow to an adjacent inlet and possibly clog things up. The angle of wave approach was changed by 5 degrees to come up with a more satisfactory annual net sand volume number.

Wrong model choice – A proposed jetty was shortened by 1000 feet based on sand transport and shoreline changes predicted by the model GENESIS. But this model is not designed to be applied to changes in sand configuration at inlets. The probable political connection is that the shortened jetties were much cheaper and hence more likely to be funded.

Failure to use available field data - In calculating longshore drift north of a jetty site, a DEAN (1991) equation-derived offshore profile was used in spite of the fact that many "real" profiles were available. The stated reason for this was that the natural profiles were too complex. The potential political advantage was the derivation of an "uncomplicated" longshore sand transport number.

Justification of projects – Geo-indicators such as the long term stability of inlets clearly point to the fact that a certain barrier island has very little longshore transport of sand. An early study of the system (using the CERC Equation) indicated a net flow of 10,000 cubic yards annually to the east on this east-west trending island. Recently an agency announced that the longshore drift was of the order of

1,000,000 cubic yards to the west. The most likely reason for this huge turn about was for the agency to blame itself for the erosion problem since the channel at the east end of the island is frequently dredged. If dredging was the cause of the erosion, funding for the project would be much easier to come by.

DISCUSSION

Coastal scientists and engineers have been working in a mindset of longshore transport volumes for several decades without looking back critically at assumptions made in pioneering studies. As a result, they have come to accept a range of sand volume numbers, stabilized by opinion of the leading experts in the field. But this range of "reasonable" numbers may well be wrong.

Both field measurements and mathematical model results are suspect for many reasons. In the field one of the major problems is the inability to measure sand transport in important storms. We question the use of models to measure the longshore transport for the following reasons; the most fundamental of which is because the nearshore system is highly complex:

- universal applicability of assumptions;
- questionable assumptions;
- unknown processes (e.g. storms);
- missing processes (e.g. storms);
- fudge factor coefficients;
- scaling up of observations (minutes to decades); and
- unverifiable results

In the use of the theoretical approach to predict the behavior of beaches or other earth surface processes it is important to recognize two kinds of models; logical models and temporal models (OERESKES, 2000) The former models answer the questions why?, how?, and what if? (THIELER *et.al*. 2000). Such modeling, often used to determine the direction or mechanics of a process, is both valid and useful. Temporal models of earth surface processes such as those described in this paper, answer the questions where?, when?, and how much?, usually for applied purposes. Temporal models are presumed to provide quantitative answers, such as volumes of sediment moved and rates of processes on a scale of accuracy sufficient to provide engineering guidance. They are coming under increasing scrutiny (SAREWITZ *et al*., 2000) because of the extreme complexity of the system that is being modeled. Almost certainly, obtaining answers of sufficient quality for engineering application is an impossible task for earth surface processes models.

CONCLUSIONS

We recommend that a great deal more attention be given to the problem of determining sand transport in the field. We also recommend that equations should not be used to determine longshore transport volumes for engineering design purposes but instead be used only in the study of the mechanics of the nearshore. Putting it another way, equations should only be used to answer the why?, how?, and what if? of longshore transport and not the where?, when?, and how much? questions.

The results of model runs should not be opaque to opponents or supporters of projects. Opaqueness can be avoided by the requirement of a straightforward discussion of assumptions, missing assumptions and the various strengths sand weaknesses of the models. Needless to say error bands are needed but error prediction requires precise and accurate models.

Sand volumes perhaps should be expressed as broad categories such as small, intermediate or large in recognition of the fact that meaningful determination of net annual transport of sand is probably impossible in this complex, dynamic and changing natural system.

LITERATURE CITED

ALLEN, J. R., 1985, Field measurements of longshore sediment transport: Sandy Hook, New Jersey,USA. *Journal of Coastal Research*, 1 (3), 231 - 240

ALLEN, J.R., 1988, Nearshore sediment transport. *Geographical Review*, 78 (2) 231-240

BODGE, K.R. and KRAUS, N.C. 1991. Critical examination of longshore transport rate magnitude. *Coastal Sediments* 91, ASCE, 139 - 155

CIAVOLA, O., TABORDA, R., FERREIRA, O. and DIAS, J.A., 1997, Field measurements of longshore sand transport and control processes on a steep meso-tidal beach in Portugal. *Journal of Coastal Research*, 13(4) 1119 – 1129

CIAVOLA, O., DIAS, N., FERREIRA, O., TABORDA, R., and DIAS, J.M.A., 1998, Fluorescent sands for measurements of longshore transport rates: a case study from Praia de Faro in southern Portugal. *Geo MarineLetters*. 18, 49 – 57

DIEGAARD, R., FREDSOE, J. and HEDEGAARD, I.B. 1986. Mathematical model for littoral drift. *Jour. Waterway, Port, Coastal and Ocean Engineering ASCE*, 112: 351-369.

DEAN, R., 1991. Equilibrium beach profiles, characteristics and applications. *Journal of Coastal Research*, 7, 53-84

DEAN, R.; BEREK, E.P.; GABLE, C.G. and SEYMOUR, R.J., 1982. Longshore sediment transport determined by an efficient trap. *Proceedings of 18th Coastal Engineering Conference (ASCE)*, 954 - 968

HANSON, H., 1989, GENESIS – A generalized shoreline change numerical model. *Journal of Coastal Research*, 5, 1-27

INMAN, D. and 5 others, 1980. Field measurements of sand motion in the surf zone. *Proceedings of 17th Coastal Engineering Conference (ASCE)*, 1215-1234

KAMPHIUS, J.W., DAVIES, M.H., NAIRN, R.B. and SAYO, O.J., 1986, Calculation of littoral sand transport rate. *Coastal Engineering*, 10, 1 – 21

KOMAR, P. and INMAN, D., 1970. Longshore sand transport on beaches. *Journal of Geophysical Research.* 75, 5514-5527

KRAUS, N., ISOBE, M., IGARASHI, H., SASAKI, T. O. and HORIKAWA, K., 1982. Field experiments on longshore sand transport in the surf zone. *Proceedings of 18th Coastal Engineering Conference (ASCE)*, 970-988.

KRUMBEIN, W.C. 1963. A geological process-response model for analysis of beach phenomena. *Bull. Beach Erosion Board*, 17, 1-15.

MASSELINK, G., and PATTIARATCHI, C., 1998. The effect of sea breeze on beach morphology, surf zone hydrodynamics and sediment resuspension. *Marine Geology*, 146,115-135

MASON, T. and COATES, T.T., 2001, Sediment transport processes on mixed beaches: A review for Shoreline management, *Journal of Coastal Research*,17, 645-657

ORESKES, N., 2000 Why predict? Historical perspectives on prediction in earth sciences. *In*: SAREWITZ, D. PIELKE, R. A. and BYERLY, R., (editors) *Prediction*, Island Press, Washington, DC, 23 - 40

PILKEY, O.H.,What you know can hurt you: predicting the behaviour of nourished beaches. *In*: SAREWITZ, D.; PIELKE, R.A. and BYERLY, R. (editors) *Prediction.* Island Press. Washington DC, 159 – 184

REDDERING, J.S.V., 1983. An inlet sequence produced by migration of a small microtidal inlet against longshore drift: the Keurbooms inlet, South Africa. *Sedimentology*, 30, 201-218.

SCHWAB, W., THIELER, R., ALLEN, J.R., FOSTER, D.S., SWIFT, B. and DENNY, J., 2000. Influence of inner continetal shelf geologic framework on the evolution and behavior of the barrier island system between Fire Island Inlet and Shinnecock Inlet, Long Island, New York. *Journal of Coastal Research*, 16, 406 – 422

SAREWITZ, D; PIELKE, R.A.and BYERLY, R. (editors), *Prediction; Science decision making and the Future of Nature*. Island Press, Covelo, California, 405 p

THIELER, E.R., PILKEY, O.H., YOUNG, R.S., BUSH, D.M. and CHEI, F., 2000. The use of mathematical models to predict beach behavior for US coastal engineering: *Journal of Coastal Research*, 16 (4), 48 – 70

USACE, 1994. *Shore Protection Manual*. Coastal Engineering Research Center, Vicksburg, Mississippi, 2 vols

WANG, P., Kraus, N.C., and Davis, R.A. 1998. Total longshore sediment transport rate in the surf zone: field measurements and empirical predictions. *Journal of Coastal Research*, 14, 269-282.

WALLACE, R.S. 1988. Quantification of net shore-drift rates in Puget Sound and the Strait of Juan de Fuca, Washington. *Journal of Coastal Research*, 4 (3), 395-403

WHITE, T.E. 1998.Status of measurement techniques for coastal sediment transport, *Coastal Engineering*, 35, 17 - 45