CHAPTER 93

LONGSHORE SEDIMENT TRANSPORT DATA: A REVIEW

by

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INTRODUCTION

Siltation rates anticipated at harbor entrances, in navigation channels and at inlet structures as well as possible adverse effects caused by these and other coastal engineering constructions are often assessed based on considerations of longshore sediment transport rates. The ability to predict the longshore sediment transport rate is consequently of considerable importance in many coastal engineering problems. The engineering need for an ability to predict longshore sediment transport rates is evidenced by the fact that the development of empirical relationships preceeded, by decades, any attempts at rigorous analyses of the mechanics of sediment transport processes in the surf zone.

A predictive relationship for longshore sediment transport rates, which enjoys considerable popularity in the United States, is the empirical relationship suggested by the U.S. Army (1973), Coastal Engineering Research Center (CERC) in their Shore Protection Manual (SPM-73). This relationship suggests the longshore transport rate, Q_ℓ, to be proportional to the wave energy flux factor, $P_{\ell s}$, and is given by the formula

$$Q_\ell = 7.5 \quad 10^3 \; P_{\ell s} \tag{1}$$

in which Q_ℓ is in cubic yards per year and $P_{\ell s}$ is evaluated based on the significant wave characteristics in the ft-lb-sec system. The wave energy flux factor is given by

$$P_{\ell s} = \frac{1}{16} \rho g \, H_b^{\,2} \, C_{g,b} \, \sin 2\theta_b \tag{2}$$

in which ρ is the fluid density, g is gravity, H, C_g and θ are the wave height, group velocity and angle of incidence, respectively, all evaluated at breaking as denoted by the subscript b.

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Earlier versions of the CERC formula suggested Q_ℓ to be proportional to some power of $P_{\ell s}$. Arguments based primarily on dimensional considerations (Bagnold, 1963) have, however, been used to justify the linear relationship suggested by Eq. (1). The absence of sediment characteristics (grain size), beach characteristics and the sole dependency of the longshore sediment transport rate on wave characteristics suggest the limited validity of Eq. (1). The data used in establishing Eq. (1) were obtained in three independent studies (Watts, 1953; Caldwell, 1956; Komar, 1969) covering a relatively wide range of conditions (grain sizes from 0.175 mm to 0.6 mm) and using quite different techniques for the determination of Q_ℓ as well as $P_{\ell s}$. Although some justification for the type of relationship suggested by Eq. (1) has been given, it should be regarded as a purely empirical relationship established by plotting points of Q_ℓ versus $P_{\ell s}$ on log-log paper. Such a plot is presented in SPM-73, and reproduced in Figure 1. Considering the fact that we are dealing with the problem of sediment transport, the data points show a remarkably low degree of scatter around the relationship given by Eq. (1). In fact, it is reported in SPM-73 that "the average difference between the plotted points from field data and the prediction given by Equation (1) is at least 28 percent of the value of the prediction". Even in the context of the much simpler problem of sediment transport in unidirectional open channel flow such an agreement between predictions and observations would be considered extremely good. Thus, one is left with the impression that Eq. (1) is a reasonably accurate relationship. Being empirical it can, however, be no more accurate than the data on which it is based. To assess the degree of confidence one can have in the data points used to establish Eq. (1) it was therefore decided to critically review the methods used by Watts (1953), Caldwell (1956) and Komar (1969) for the determination of Q_ℓ and $P_{\ell s}$.

The review emphasizes a critical evaluation of the different methods used for the determination of the longshore sediment transport rate. The assumptions underlying the use of a particular method are discussed and the degree to which these assumptions are violated or not is investigated from the reported data. It is realized that there are several unanswered questions regarding the validity of the significant wave concept as an equivalent representation of a random sea. This problem is not addressed in the review of the manner in which the wave energy flux factor was determined. Comments on the determination of wave characteristics are therefore limited to comments on how the significant wave characteristics were obtained and used to determine the wave energy flux factor.

REVIEW OF THE DATA BASE

WATTS (1953)

In this study a sediment trap north of the jettied South Lake Worth Inlet on the east coast of Florida was assumed to catch the long-

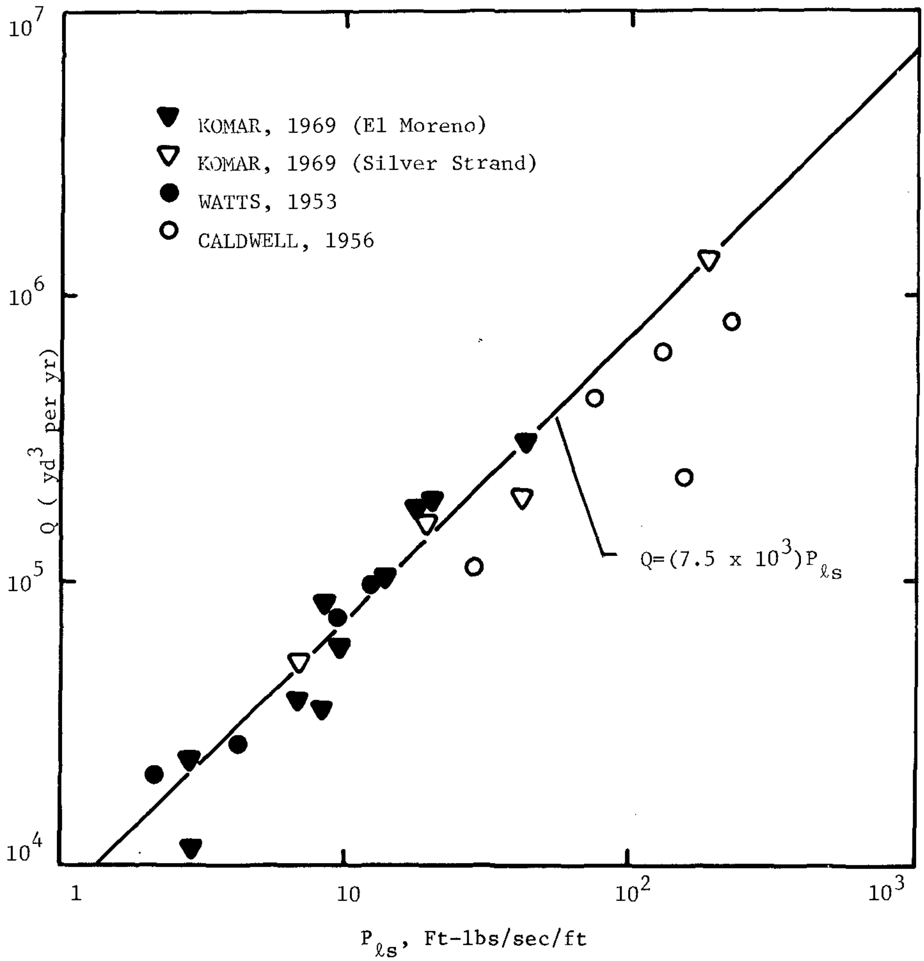

Figure 1: Plot of Data Points and Empirical Relationship for Longshore Sediment Transport Rates. (From U.S.Army, Shore Protection Manual, 1973)

shore sediment transport during periods of waves out of the north. The rate of southerly transport was estimated from pumping rates reported by a sand by-passing plant at the inlet. Wave heights and periods were obtained at 4-hour intervals from a wave gage located in 17 ft. of water some 10 miles north of the study area. Wave directions were determined twice daily by sighting from the top of a hotel 3.5 miles north of the study area using an engineer's transit. The estimated pumping rate over a given time interval, Q_ℓ, was related to the southerly wave energy flux, P_ℓ, during the same interval. Both short term ("daily" averages) and long term ("monthly" averages) were reported. Only the monthly averages (4 points) are used in SPM-73 to establish Eq. (1).

The use of a sand trap to determine longshore sediment transport rates is, in principle , appealing. The method does, however, rely on several assumptions some of which are discussed in the following.

(A) For waves out of the north the sand trap must be 100 percent effective and catch only the longshore transport.

In general it appears to be extremely difficult to ascertain whether or not this assumption is violated. During Watts' experiment wave heights were quite moderate (2 ft. or less) which may justify assumption (A) provided the trap caught only the longshore transport.

(B) For waves out of the south the sand trap should not catch any significant amount of material.

If significant amounts of sediment are caught by the sand trap during periods of waves out of the south this is indicative of the sand trap catching not only longshore transport. Presumably, this would also be the case during periods of waves out of the north, thus violating assumption (A). In the analysis of the data averaged over long periods Watts correlated the total pumping rate with the wave energy flux factor computed from wave observations including only the energy flux during times of waves out of the north. This clearly makes the monthly average data meaningful only if assumptions (A) and (B) are satisfied.

(C) Erosion north of the jetty during periods of waves out of the south does not affect the longshore transport rate when waves are out of the north.

If it is assumed that the jetties act as a littoral barrier for waves out of the south, the beach north of the inlet is deprived of sediment during periods of waves out of the south. To the north of the jetty there would be a stretch of beach along which the longshore sediment transport would be increasing with distance from the jetty until it attains its equilibrium value. This would cause some erosion to take place north of the jetty during periods of waves out of the south. Once the wind and waves swing around to be out of the north, a southerly transport would be initiated. If this southerly transport is affected by the erosion which took place during waves out of the south, by repairing the damage done, the sand trap would not catch the southerly longshore transport until equilibrium conditions were re-established. It apears to be extremely difficult to ascertain to which extent assumption (C) is violated; however, the use of sand traps for the determination of longshore sediment transport rates relies heavily on this assumption.

To examine the degree to which the assumptions discussed above are violated in the field experiment performed by Watts the complete tabulation of wave data given by Das (1971) as well as the pumping rate reported by Watts (1953) have been plotted in Fig. 2. The sign covention for angles of incidence, θ, is that $\theta > 0$ for waves out of the north. At the start of the experiment, it is seen that the waves were quite high (H^2) as were the pumping rates (Q). During the period of March 7 to 9 waves were out of the north ($H^2 \sin\theta > 0$) but swung around to be out of the south from March 10 to 15. From the ideal behavior of the sand trap discussed in conjunction with assumption (B) it is noted that the change in wave direction, somewhat disturbingly, is practically unnoticeable in the reported pumping rate during this period. Similar evidence of significant transfer of sediment into the sand trap during periods of waves out of the south is observed around March 23, April 10, and April 24. The conclusion reached from the presentation of Watts' data in Fig. 2 is that assumption (B) is violated, thereby invalidating the the manner in which the data points corresponding to monthly averages were obtained. Furthermore, the results presented in Fig. 2 suggest that the sand trap may catch sediment not considered to be part of the longshore sediment transport during periods of waves out of the north. Thus, the daily averages, obtained over the periods indicated in Fig. 2, may not represent the short term longshore transport. In addition, the short term average pumping rates are more sensitive to errors arising from pumping rates not corresponding exactly to the amount of material deposited in the sand trap.

The wave data (height and period) were obtained in 17 ft. of water. No specific mention of the depth of water where the wave direction was obtained can be found in the original report. Since the direction was observed visually it would be tempting to assume that the direction was the angle of incidence at breaking. Several directional observations, however, report values of θ in excess of 20° (up to 49°). Since waves of 5 sec. period breaking in 1.5 ft. of water will have an angle at breaking less than 15°, it does not appear reasonable to assume that the reported angle of incidence corresponds to the angle at breaking. Examining the nature of Eq. (2) this may be written in the form

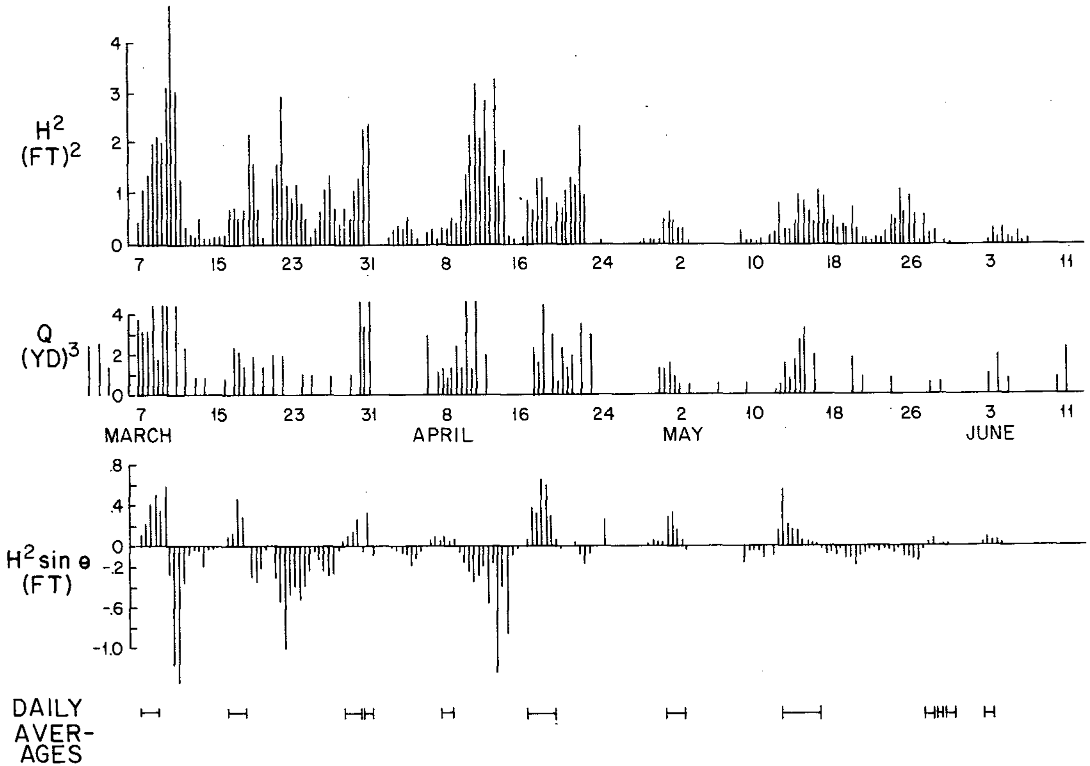

Figure 2: Plot of Wave Intensity (H^2), Pumping Rates (Q), and Directional Wave Intensity ($H^2 \sin\theta$) During Watts' (1953) Experiments.

$$P_{\ell s} = \{\frac{1}{8}\,\rho g\, H_b^{\;2}\, C_{g,b}\, \cos\theta_b\}\, \sin\theta_b \tag{3}$$

The bracketed terms represent the shore normal energy flux and assuming Snell's Law to be valid this quantity is customarily assumed to remain constant. Thus, the bracketed terms may be evaluated in any water depth, for example, corresponding to h = 17 ft. where H and T were obtained. The uncertainty about the location where θ, as reported by Watts, was obtained is of relatively minor importance in the evaluation of the bracketed term in Eq. (3). It is, however, of extreme importance that the angle at breaking be used to evaluate $\sin\theta_b$. It is evident that Watts evaluated Eq. (3) using a water depth of 17 ft. and assuming all wave parameters to correspond to this water depth. If the reported value of θ does indeed correspond to h = 17 ft. Watts' evaluation of $P_{\ell s}$, which is used in SPM-73, could potentially be off by a factor of the order 5.

CALDWELL (1956)

In this study the erosion rate "downdrift" of a littoral barrier was determined by surveying 21 transects spaced at 500 ft. intervals. Surveys were repeated every 2 to 3 months. The net amount of sediment volume change within the study area between consecutive surveys was used to determine an average daily net sediment transport rate at the transect furthest away from the littoral barrier. Wave characteristics were determined from a combination of wave gage records, obtained 6 miles away in 20 ft. of water, and from hindcasts. Wave direction was obtained from refraction diagrams based on hindcast deep water wave characteristics. This study produced six points of Q_ℓ versus P_ℓ; however, one of these points showed a negative relationship between Q_ℓ and P_ℓ and it was consequently discarded.

Using the erosion or deposition rate "downdrift" of a littoral barrier to quantify the longshore sediment transport rate is based on the assumptions that

(D) The littoral barrier is 100 percent effective.

(E) No transport out of or into the study area through its offshore boundary.

(F) The longshore sediment transport through the downdrift boundary of the study area is unaffected by the presence of the littoral barrier.

As discussed in conjunction with the discussion of assumption (C), the longshore transport rate requires some distance downdrift of a littoral barrier to achieve its equilibrium value. The same applies for sediment transport towards the littoral barrier. The spatially varying longshore sediment transport rate in the vicinity of the littoral barrier suggests an erosion or deposition pattern which approaches a zero volume change between transects close to the "downdrift" boundary of the study area. This required behavior of the erosion pattern appears self-evident since the net volume change within the study area and hence the inferred longshore transport rate otherwise would depend on the location of the "downdrift" boundary.

The observed volume changes within the study area of Caldwell are plotted in Fig. 3 for the six survey periods. It is evident that the erosion patterns for all survey periods conform rather poorly to the expected ideal pattern discussed above. Only the erosion and deposition patterns during the survey periods Nov. 9 to Jan. 25 and Jan. 25 to April 8 exhibit the features resembling those required. The two data points corresponding to these survey periods, with $P_{\ell s}$ evaluated in the manner to be discussed, happen to indicate a significant decrease in Q_{ℓ} with increasing $P_{\ell s}$, hardly a comforting result.

The wave characteristics (height and period) were determined from a combination of wave gage measurements in 20 ft. water depth and hindcasts, used whenever results from the wave gage were unavailable. A comparison between hindcast and measured wave characteristics is reproduced in Table 1.

Table 1: Comparison between hindcast and observed (wave gage) wave heights (from Caldwell, 1956, Table 4).

H_{gage} (ft.)	3.6	0.5	2.0	1.1
$H_{hindcast}$ (ft.)	1.4	1.5	1.5-1.8	1.5

Recalling that the wave height enters the determination of $P_{\ell s}$, Eq. (2), essentially to the 5/2 power, it is seen from the comparison of measured and hindcast wave heights that $P_{\ell s}$ obtained from hindcast wave characteristics may deviate considerably from the values obtained from measured wave characteristics.

Refraction diagrams were used to determine the wave directions in 12 ft. water depth for waves out of the west to northwest and for waves out of the south. For waves out of the west to northwest hindcast directions varying between 4^o to 15^o were obtained, and an "average" value of $\theta = 9^o$ was used for all waves from this direction. For hindcast waves out of the south an average direction of 21^o, representing a directional spreading of $16^o < \theta < 23^o$, was used for all waves.

The value of the wave energy flux factor was evaluated from Eq. (2) using the hindcast or observed wave height and period corre-

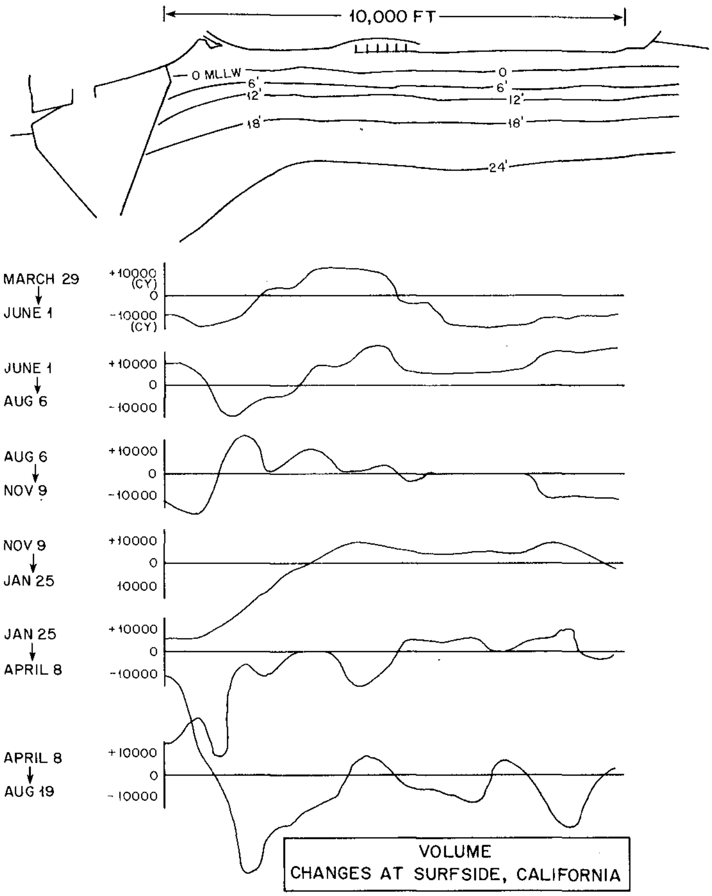

Figure 3: Plot of Volume Changes Observed During Caldwell's (1956) Experiments.

sponding to 20 ft. water depth with the angle θ taken as the constant average value determined from refraction diagrams and corresponding to a water depth of 12 ft. Thus, the values obtained by Caldwell for $P_{\ell s}$ are not based on breaking wave characteristics, and Caldwell's values can readily be imagined to be off by factors of 10 or more. Nevertheless, the values for $P_{\ell s}$ obtained by Caldwell (1956) are the values used in the SPM-73 plot of Q_ℓ versus $P_{\ell s}$.

KOMAR (1969)

In this study sand tracers (fluorescent) were injected on the beach face (El Moreno Beach) or across part of the surf zone (Silver Strand Beach). Sampling at some time following injection gave contours of equal tracer concentration from which the centroid movement of the tracers was determined. From the distance traveled, $\Delta\ell$, and the time, Δt, the average centroid velocity, $V = \Delta\ell/\Delta t$, was obtained and used as the average velocity of moving sediment. The longshore transport rate was then obtained from the formula

$$Q_\ell = V\, b\, X_B \tag{4}$$

in which b is the thickness of the moving layer of sediment and X_B is the width of the surf zone. The thickness of the moving layer was taken to be the burial depth of tracers as obtained from core samples taken close to the injection line. Wave characteristics were determined from a wave gage array located some distance seaward of the surf zone. Breaking wave characteristics were either predicted by shoaling the measured waves until breaking or by direct observation of the breaker characteristics.

When applying tracer techniques for measuring sediment transport a number of assumptions are made.

(G) The tracer should behave as the native material.

This is most readily satisfied by coating material from the study area as done by Komar.

(H) The transporting system is stationary.

This basically requires conditions to be steady during the experiment. Clearly, conditions are far from steady in the surf zone. However, one may view the transport process in the surf zone as consisting of a series of events, each event corresponding to the passage of a breaking wave. The stationarity requirement therefore does not apply to the time scale of the wave motion. Rather it should be interpreted to mean that wave conditions do not change during the experiment. At Silver Strand Beach injection was made in the surf zone around high tide and sampling was performed 1 to 3 hours after injection. Although the tide introduces some changes during the duration of an experiment of this type, it appears that this lack of stationarity is minimized by conducting the experiments in the manner used by Komar at Silver Strand Beach. At El Moreno Beach, the experimental procedure was, however, somewhat different. Here the tidal range is considerable (about 20 ft.) so the steep beach face was exposed during low tide. Tracer was injected in a trench on the beach face during low tide. As the tide came in the surf zone would move across the injection site. The same would happen as the tide went out. When the beach face was exposed again sampling was performed. It is evident that the conditions during experiments at El Moreno Beach hardly can be considered to have been stationary. We are not aware of any investigations which allow us to assess the possible effects of lack of stationarity on results obtained from tracer experiments. All we can say is that the crucial assumption (H) was violated for Komar's experiments on El Moreno Beach and the quality of his data on sediment transport rates obtained at this location is therefore somewhat uncertain.

An additional assumption is that

(I) Sufficient time following injection should be allowed to ensure that the tracer behavior is independent of the manner in which it was introduced.

If one models tracer dispersion based on the diffusion equation the spatial integration method used by Komar was shown by Lean and Crickmore (1963) to be applicable at any time following injection. The dispersal patterns observed by Komar are, however, not indicative of a transport system which is adequately modeled as a simple advective diffusion process. If this were the case the region of high tracer concentrations would move downdrift and at the same time spread out. Contrary to this behavior many of Komar's dispersal patterns show that the area of high tracer concentrations, at the time of sampling, had remained at the location of the initial injection. Such a behavior of tracer dispersal following an instantaneous line injection is to some extent modeled by a simple model which considers the transporting system to consist of two layers. In this two-layer model the top layer is a transporting layer and exchanges particles with an immobile bed layer. Based on a model of this type tracer particles would appear in the bed layer downdrift of the injection site because they had been "picked up" by the transporting layer and subsequently deposited in the bed layer. This two layer model predicts that the area of high tracer concentration in the bed would remain at the injection site for some time following time of injection. It also predicts that the centroid velocity immediately following injection is zero and with time approaches a constant value. If the centroid velocity obtained by Komar corresponds to this equilibrium value the two layer model suggests that the transport indeed may be obtained from Eq. (4). The only change from a diffusion model is that b, rather than being interpreted as the thickness of moving sediment, should be interpreted as the thickness of the non-moving bed layer which exchanges tracer particles with the moving layer. It is not possible to ascertain whether or not the time between injection and sampling used by Komar at Silver Strand Beach was sufficient to satisfy assumption (I). The determination of V obtained from a single measurement of $\Delta\ell/\Delta t$ can therefore not be accepted without some reservation.

Since the longshore transport rate represents the transport across the entire width of the surf zone it is, of course, necessary that the entire surf zone participates in the dispersal of the tracer particles. A certain distance must therefore be allowed downdrift of the injection site for complete mixing to take place, if the injection covers only part of the width of the surf zone. Komar (1969) comments on this point in conjunction with a discussion of the uncertainties associated with his experiments at Silver Strand Beach.

A final requirement, when tracer techniques are used in sediment transport studies, is that all the tracer particles initially injected must be accounted for. In the context of Komar's longshore sediment transport study this translates into the assumption that there can be

(J) No transport of tracer particles out of the sampling area.

The degree to which this assumption was satisfied in Komar's experiments was assessed by evaluating the amount of tracer accounted for by the sampling program. It is, however, difficult to interpret the significance of a tracer mass balance which accounts for, say, 80 percent of the tracer initially injected. Is the discrepancy experimental error or did tracer particles leave the sampling area? And, if the latter explanation is adopted, to which extent does this loss of tracers affect the results obtained?

The quantity b in the transport equation, Eq. (4), was obtained by Komar from core samples. The values obtained for b in a single experiment were reported to vary greatly with location of the core sample relative to the initial injection line. Thus, Komar reports that fairly large burial depths of tracers could be observed near the injection site whereas tracers were found only near the bed surface further away from the injection. This observed variation in b necessitates a choice of which value to use in the evaluation of Eq. (4). The larger burial depth observed close to the injection site is explained by Komar to be associated with the relative abundance of tracers in this region over a relatively long period of time. Thus, near the injection site tracers are more likely to have sufficient time to "diffuse" vertically into the bed. This explanation does appear very plausible indeed. It does not, however, appear to justify Komar's use of the large values of b obtained close to the injection site when Eq. (4) is evaluated. It is our feeling that the determination of b represents one of the major difficulties in sediment transport studies using tracer techniques.

Komar's determination of the wave energy flux factor, as defined by Eq. (2), appears to be quite accurate when one accepts the equivalent wave concept without detailed considerations of the influence of directional wave characteristics.

CONCLUSIONS

The data base used by the U.S. Army (1973) in their SPM-73 to establish the empirical longshore transport relationship given by Eq. (1) has been reviewed.

The review revealed that the data points obtained from the studies by Watts (1953) and Caldwell (1956) are of questionable quality. Fundamental assumptions regarding the methods used for the determination of the longshore sediment transport rates appear to have been violated to the extent that one can have no confidence in the values of Q_ℓ reported in these studies. The values obtained for the wave energy flux factor should, according to Eq. (1), correspond to breaking wave conditions. The values of the wave energy flux factor reported by Watts (1953) and Caldwell (1956) are used in SPM-73 as if they corresponded to breaking wave conditions whereas they in fact do not. It is not possible to quantify the errors associated with each of the data points obtained by Watts and Caldwell. However, they appear to be sufficiently uncertain in terms of both Q_ℓ and $P_{\ell s}$ to justify their exclusion from any analysis aimed at establishing empirical longshore sediment transport relationships.

Removing Watts' and Caldwell's data from Fig. 1 leaves the data points obtained by Komar (1969) and removes the comfort of the argument that Eq. (1) is based on data from three independent studies. The degree of confidence one can have in the accuracy of Eq. (1) is therefore intimately related to the accuracy of the methodology used by Komar in his experiments. The critical review of Komar's use of tracer technology for the determination of longshore sediment transport rates revealed that several of the basic assumptions underlying the use of tracers in sediment transport studies appear to have been violated in this study. The lack of stationarity of the transporting system during the experiments at El Moreno Beach renders the quality of these data points uncertain. The uncertainty about whether or not sufficent time was allowed between injection and sampling to make the determination of the centroid velocity meaningful during the experiments at Silver Strand Beach casts doubts on the accuracy of these data points. In all experiments the ambiguity in the determination of the "thickness of moving sand" introduces a significant uncertainty in the results obtained. It does not appear possible to quantify the magnitude of the errors resulting from the noted violations of the basic assumptions. The fact that several basic assumptions were violated does, however, suggest that it is unjustified to rely too heavily on the accuracy of the sediment transport rates obtained in Komar's investigation.

The conclusion of our review is therefore that coastal engineers using Eq. (1) for the calculation of longshore sediment transport rates should regard their results as no better than order of magnitude estimates.

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