CHAPTER 50

A GROSS LONGSHORE TRANSPORT RATE FORMULA

by

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ABSTRACT

Gross longshore transport rates for 11 long-term field measurements are predicted reasonably well by the empirical relation, $Q=2H^2$, where Q is longshore transport rate in 100,000 yd^3/yr, and H is a mean breaker height in feet. A physical explanation of this empirical relation assumes: (1) most littoral drift is transported in suspension; (2) longshore current velocity is predicted by $V = gmT\sin 2\theta_b$; (3) the empirical relation is an equation for conservation of suspended sediment in the longshore current.

INTRODUCTION

Definitions. Littoral drift is the material moved in the littoral zone by waves and currents. For this paper, the littoral zone is a strip which follows the shoreline, bounded by the runup limit on the landward side and by a depth on the seaward side at which large waves begin to move bottom sediment in significant quantities.

The rate at which littoral drift is moved parallel to the shoreline is the longshore transport rate. Since this rate is directed parallel to the shoreline, there are two possible directions of motion, which may be called the right and left directions, if defined for an observer standing on the shore looking out to sea. Anything moving from the observer's right to his left is moving in the left direction, indicated by the subscript $_\ell$. A similar definition holds for the right direction, indicated by the subscript $_r$.

A gross longshore transport rate is defined for a given point on a shoreline as the sum of the amounts of littoral drift transported to the right and to the left, past that point on the shoreline, in a given time period.

Similarly, a net longshore transport rate is defined as the difference between the amounts of littoral drift transported to the right and to the left, past that point on the shoreline, in a given time period.

Longshore transport rates are usually given in units of volume per time (cubic yards per year in the U.S.). Typical rates for oceanfront beaches range from 10^5 to 10^6 yd^3/yr. These volumes include about 40% voids and

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about 60% solids. The solids commonly are fine to medium sand-sized material, either quartz with a specific gravity of 2.65, or carbonates or silicates with slightly higher specific gravities.

It is convenient to indicate the longshore transport rate by the symbol Q. Then, the gross longshore transport rate, Q_g, is, by definition,

$$Q_g = Q_r + Q_\ell \tag{1}$$

where Q_r is the transport to the right and Q_ℓ is the transport to the left. Similarly, the net longshore transport rate, Q_n, is

$$Q_n = Q_r - Q_\ell \tag{2}$$

The quantities Q_r, Q_ℓ, Q_n and Q_g all have specific engineering uses: Q_g is needed to predict shoaling rates in uncontrolled inlets; Q_n is needed for design of protected inlets and for predicting beach erosion on the open coast; Q_r and Q_ℓ are needed for design of jetties and impoundment basins behind weir jetties. In addition, Q_g provides an upper bound on the other quantities since, by (1) and (2), $Q_g \geq Q_n$. Note that $Q_g = |Q_n|$ if either Q_r or Q_ℓ is zero, as may happen on partially sheltered coasts.

Purpose. This paper presents an empirical relation between gross longshore transport rate, Q_g, and the local mean breaker height, H, as a first approximation for engineering predictions. An hypothesis is also presented to explain the empirical relation.

Present (1970) Practice. Longshore transport rates are predicted by the following methods:

1. The best way to predict longshore transport rate at a given site is to adopt the best known rate from a nearby site, with modifications based on local conditions.

2. If rates from nearby applicable sites are not known, then the next best way to predict transport rates at a given site is to compute them from data showing historical changes in the topography of the littoral zone (charts, surveys, and dredging records are primary sources).

3. If neither Method 1 nor Method 2 is practical, then it is accepted practice to use either measured or calculated wave conditions along with the curve relating "Longshore component of wave energy and Littoral transport rate" which appears in CERC Technical Report Number 4 (Coastal Engineering Research Center, 1966, Figure 2-22, p. 175).

Method 1, if applicable, depends largely on engineering judgement. Method 2, if applicable, is a straight-forward, but tedious, application of historical data, which gives useable answers, provided the basic data are reliable, the calculations are correct, and the interpretation is based on a thorough knowledge of the locality. By choosing only a few representative wave conditions, Method 3 can usually supply an answer with less work than Method 2, but with correspondingly less certainty. Because calculation of needed wave statistics in Method 3 follows an established routine, it is often easier than researching the records and computing the changes necessary for Method 2. Thus, there is a tendency to apply Method 3 where possible.

Transport Rate - Energy Flux Correlation. The curve on which Method 3 is based (CERC, 1966, p. 175), taken from Savage (dashed line of Figure 7 in Savage, 1962), shows a correlation between longshore transport rate and energy flux. Savage's dashed line is his modification, based on laboratory data, of an earlier curve given by Caldwell (1956) that is based on two sets of field data (Caldwell, 1956; Watts, 1953) which are generally accepted as the best prototype longshore transport data now (1970) available. The curves of both Savage and Caldwell, as adapted from Savage (1962), are shown on Figure 1 of this paper.

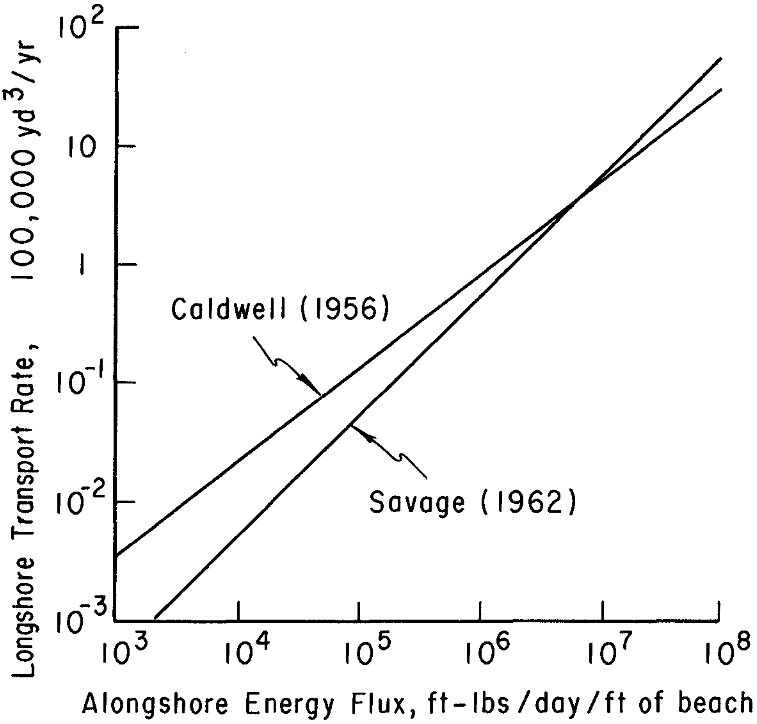
The variables plotted on Figure 1 are Caldwell's adaption of a somewhat cryptic suggestion in the fifth appendix of an unpublished report prepared by the Los Angeles District, Corps of Engineers (dated October 1, 1948; see also Eaton, 1951). It appears probable that the suggestion in the 1948 report was, in turn, based on work done at the Scripps Institution of Oceanography shortly before that date (S.I.O., 1947).

The relation shown on Figure 1 has been criticized (Galvin, 1963; Longuet-Higgins, private communication, 1969; Komar and Inman, 1970) for, among other things, confusing scalar energy with vector energy flux. See, for example, the legend on the horizontal axis of Figure 2-22 in TR4 (CERC, 1966, p. 175). However, for the practicing engineer looking for an answer to his problem, this objection is a mere quibble, provided that the straight line gives a reasonably accurate answer. Although the present state of the art is such that a reasonably accurate answer is one good within a factor of 2, it is doubtful that the relation on Figure 1 is that good. Thus, further work on the subject is justified.

GROSS TRANSPORT RATE FORMULA

Empirical Relation. It appears intuitively obvious that the longshore transport rate, Q, must be closely related to wave height at breaking, H. On a naive level, the bigger the waves, the more energy they have to move sand around. Or the bigger the waves, the greater the cross-sectional area of the surf zone through which the sediment might move. Thus, a relation between drift rate and breaker height is expected, and, indeed, such a relation already exists in the longshore transport curves of Caldwell and Savage, since the horizontal axis of Figure 1 is a term including H^2.

At the Coastal Engineering Research Center (CERC), visual observations of waves along U.S. coasts are routinely collected as a first step towards



TRANSPORT RATE - ENERGY FLUX CORRELATION

Figure 1

defining the wave climate of these coasts. Much of these data are collected by Coast Guard personnel or other volunteers in the Cooperative Surf Observation Program (COSOP), the Beach Evaluation Program (BEP), and the Littoral Environmental Observation Program (LEO). (See Darling, 1968; Galvin, et al., 1969, 1970; Szuwalski, 1970). There is also an extensive program of wave gaging on U. S. coasts (Darling and Dumm, 1967).

Also at CERC, there is frequent occasion to discuss coastal engineering problems requiring information on longshore transport rates for U. S. coasts, many of which are tabulated by Johnson (1957). Familiarity with these wave and transport data impressed on the writer that measured transport rates and observed mean breaker heights are highly correlated on U. S. coasts. This led to the following empirical relation. If longshore transport rate, Q, is plotted against mean breaker height, H, a curve given by

$$Q = 2H^2 \tag{3}$$

forms an envelope (Figure 2) over all but two known (Q,H) pairs, when Q is in units of 100,000 yd^3/yr and H is in feet.

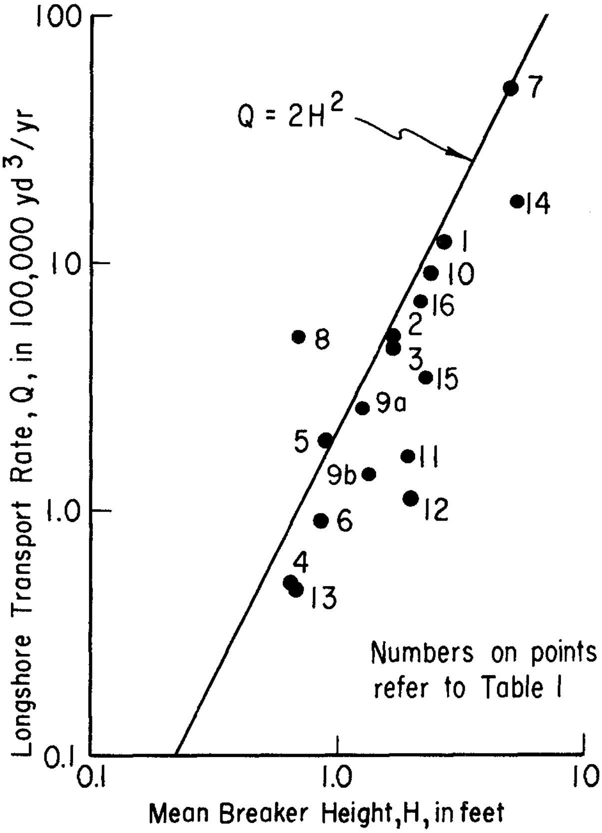
The Data. The 17 longshore transport rates plotted on Figure 2 and tabulated in Table 1 include rates obtained from 13 Corps of Engineer field studies (points 1 through 10, and 15 and 16). All but one of these 13 rates (point 9b) are based on changes measured by Method 2 for periods of at least one year. Three other shorter field studies are plotted, including two tracer studies (points 11 and 12) and one special study (point 14), all having durations measured in hours or days. One laboratory point (14) is plotted, which is the maximum transport rate obtained by Fairchild (1970).

The plotted transport rates are all supposed to be gross transport rates. In some cases, the sources report the data as gross rates, or as nearly gross rates. In the three short-term field studies (points 11, 12, and 14) and in the single laboratory case (point 13), the source description leads to the assumption that gross rates are involved. For point 16, the source (Committee on Tidal Hydraulics, 1964) give Q_ℓ and Q_r, so equation (1) was used. Point 6 (southwest Lake Michigan) is the maximum of 6 values of Q_n given by Johnson (1957), assuming from equations (1) and (2) that $Q_g \geq Q_n$.

For points 9a, 9b, and 10, only the net rates were given, but gross rates were computed from the net rates by equation (4),

$$Q_g \approx Q_n(1+\alpha)/(1-\alpha) \tag{4}$$

which is obtained by dividing equation (1) by (2) and defining $\alpha=Q_\ell/Q_r$. In these cases, the gross rates were calculated by assuming that the ratios of waves from the south to waves from the north (points 9a and 9b from Watts, 1953b) and the corresponding ratio of longshore energy fluxes (point 10 from Caldwell, 1956) were identical to α in (4). Note that equation (4) is not useful when α approaches 1, i.e., when the net transport rate is a small fraction of the gross transport rate.



EMPIRICAL PREDICTION OF
GROSS LONGSHORE TRANSPORT RATE
Figure 2

GROSS LONGSHORE TRANSPORT RATES

No.	Locality	Measured ($10^5 yd^3/yr$)	Predicted($2H^2$) ($10^5 yd^3/yr$)	H (ft)	Sources for Data* Transport Rate	Sources for Data* Height
1	Port Hueneme	12	15.1	2.75	Herron & Harris, 1966.	LEO & Gage 715,1962
2	Sandy Hook	4.93	5.7	1.69	Caldwell, 1966	COSOP (Monmouth Beach)
3	Fire Island Inlet	4.50	5.8	1.70	Taney, BEB TM 128	COSOP (Short Beach)
4	Tampa Bay Entrance	0.50	0.87	0.66 0.66	Jacksonville Dist. and Caldwell	COSOP (Cape San Blas) Naples Wave Gage (59-60)
5	Presque Isle	1.91	1.6	0.9	Berg	Saville, BEB TM 37
6	SW L. Michigan	0.90	1.5	0.87	Johnson, 1957	Saville, BEB TM 36
7	Columbia R. Estuary	50	50.0	5.01	Caldwell	COSOP (Yaquina Bay)
8	Galveston	3.30	1.0	0.70		Gage (Apr, May, 47)
9a	Lake Worth	2.5	3.2	1.26	Watts, BEB TM 42	COSOP(Hillsboro,all year)
9b	S. Lake Worth	1.37	3.6	1.34	Watts, BEB TM 42	COSOP(Hillsboro in Mar, Apr, May)
10	Anaheim	8.85	11.5	2.40	Caldwell, BEB TM 68	Huntington Beach Gage
11	Virginia Beach	1.60	6.5	1.80	Boon, 1969	Harrison, 1968
12	El Moreno	1.10	8.0	2	Komar, 1969	Komar, 1969
13	CERC Lab	0.48	0.92	0.68	Fairchild, 1970	Fairchild, 1970
14	Cape Thompson	17.1	60.5	5.5	Moore and Cole, 1960	Moore and Cole, 1960
15	Carolina Beach	3.4	10.1	2.25	Wilmington District	COSOP (Atlantic & Oak Island averaged)
16	Ponce de Leon	7.0	9.2	2.15	Com. on Tidal Hyd.	COSOP (Ponce de Leon)

*COSOP: CERC-US Coast Guard Cooperative Surf Observation Program. Nearest open coast station given in ( ).

*LEO: CERC Littoral Environment Observation Program, from Berg and Szuwalski.

The wave data plotted on Figure 2 and tabulated in Table 1 are mean values of the height of waves breaking or shoaling on beaches. Of the 17 plotted points, 12 are based at least in part on visual estimates of breaker height. These include 8 COSOP heights, one LEO height, and 3 heights from published sources (see Table 1). The COSOP heights are simple averages of all observations available from the locality listed. The minimum length of record for any of the 8 COSOP localities is 4 years. Each observation is a visual estimate of the height of the highest one third of the waves breaking on the beach. Other work (Galvin, et al., 1969; Galvin, et al., 1970) has shown that mean annual heights obtained in this way are internally consistent and that the distribution of these heights around the U. S. coasts agrees with known climatic conditions.

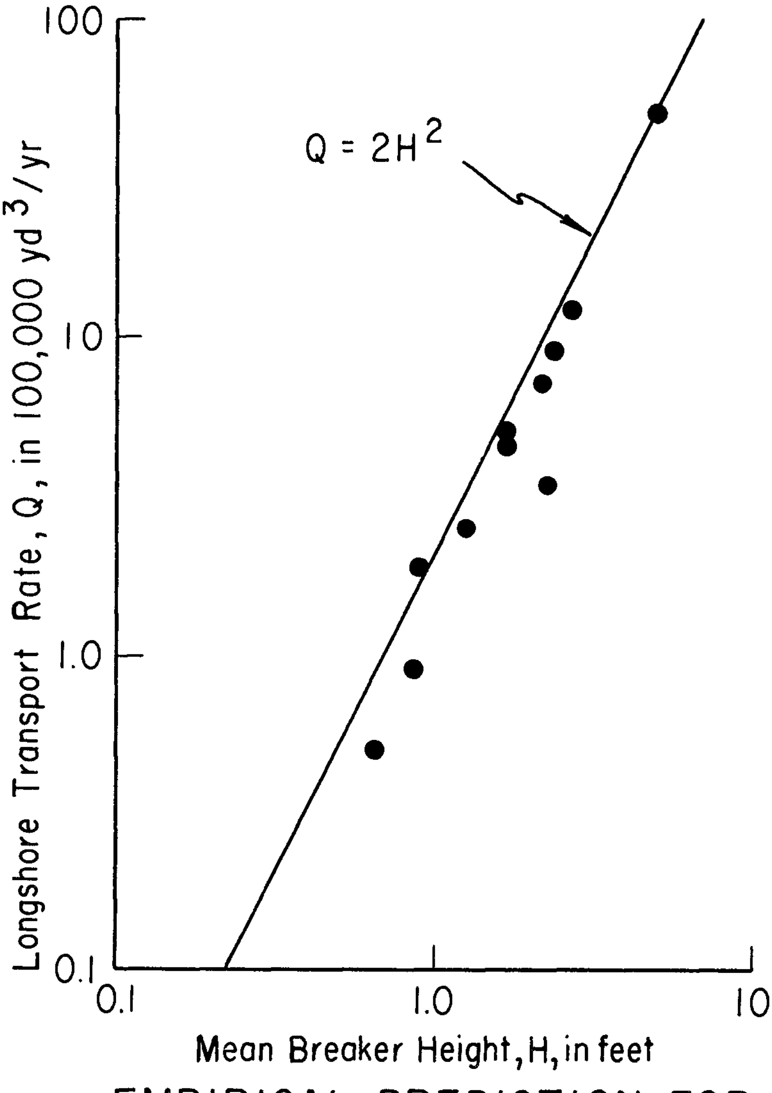
Five sets of wave gage records are used, including one set from laboratory wave gages for point 13. Two gage records have not been shoaled to the breaking point, although all were obtained in fairly shallow water. The two data points from the Great Lakes (points 5 and 6) use wave heights from hindcasts by Saville (1953a; 1953b), taken from the percent of total time curves, including the effect of ice cover, but not shoaling to the breaking point. The wave height for point 12 from Komar's (1969) tracer study is listed as 2 feet, but the author gives only the range of wave heights observed (1 to 3 feet).

In all cases, the best available wave height data were chosen, with measured or visually observed values given preference over hindcast values. Where it is possible to compare data from different sources, the data usually agree. For example, the visual and unshoaled gage data for point 4, Table 1, are precisely, although accidentally, equal.

In the case of point 15, the height listed is the average of the nearest COSOP stations from either side of Carolina Beach, North Carolina - Oak Island to the south where the H is 1.18 feet, and Atlantic to the north where the H is 3.32 feet. Despite this disparity, which is caused by differing exposure of the localities, the mean of the two COSOP stations agrees well with four months of visual and gage records obtained at Wrightsville Beach, only a few miles from Carolina Beach.

Long-term Rates. The 17 points on Figure 2 are not all on the same basis, particularly in terms of length of record. For this reason, only the (Q,H) pairs for which both the Q and the H data are based on more than one year of record have been plotted in Figure 3. It then becomes obvious that, in eliminating data based on shorter lengths of record, a significant amount of the scatter in Figure 2 is also eliminated. This reduction of scatter by elimination of shorter term data increases confidence in equation (3) as an empirical prediction of gross longshore transport rates.

Of the 6 shorter term points that have been eliminated in going from Figure 2 to Figure 3, the two that fall furthest below the curve are the only two tracer tests in Table 1 (points 11 and 12). If there is validity to the empirical relation (3), then the fact that points 11 and 12 have significantly lower rates of drift than is predicted by (3) is consistent with the hypothesis that the burial and delayed erosion of tracers produce indicated transport rates lower than actual rates (Galvin, 1965).



EMPIRICAL PREDICTION FOR LONG TERM RATES

Figure 3

It is emphasized that the field data plotted on Figure 2 and tabulated in Table 1 include all known (Q,H) pairs for which Q equals, or nearly equals, Q_g. That is, the plotted and tabulated transport rates are intended to be gross rates only. There are many more (Q,H) pairs where Q equals Q_n when $Q_n < Q_g$. In all of these Q_n cases, the (Q,H) pairs plot below the curve given by equation (3), so that the equation, $Q=2H^2$, is really an envelope above the measured longshore transport rates.

Instead of this envelope, a better fit of the curve to the gross transport data on Figure 3 could be had by changing the constant 2 in equation (3) to 1.5. However, historical estimates of longshore transport rates, somewhat like estimates of the age of the earth, are nearly always revised upward and only rarely revised downward. Therefore, it is safer, as well as more convenient, to keep 2 as the constant in equation (3).

PHYSICAL HYPOTHESES

Energy Flux. The simplicity of equation (3) and the unexpected, but empirically good, fit of the data to it prompt an attempt at a physical explanation. The fact that H enters equation (3) as a squared term suggests that energy flux may be involved. However, since H is defined as the breaker height, the energy flux ought to depend on $H^{5/2}$, assuming that the energy density is proportional to H^2 and that the group velocity depends on $H^{1/2}$ near breaking. But the slope of the H^2 curve seems to fit the data better than the slope of an $H^{5/2}$curve (compare Figures 3 and 4).

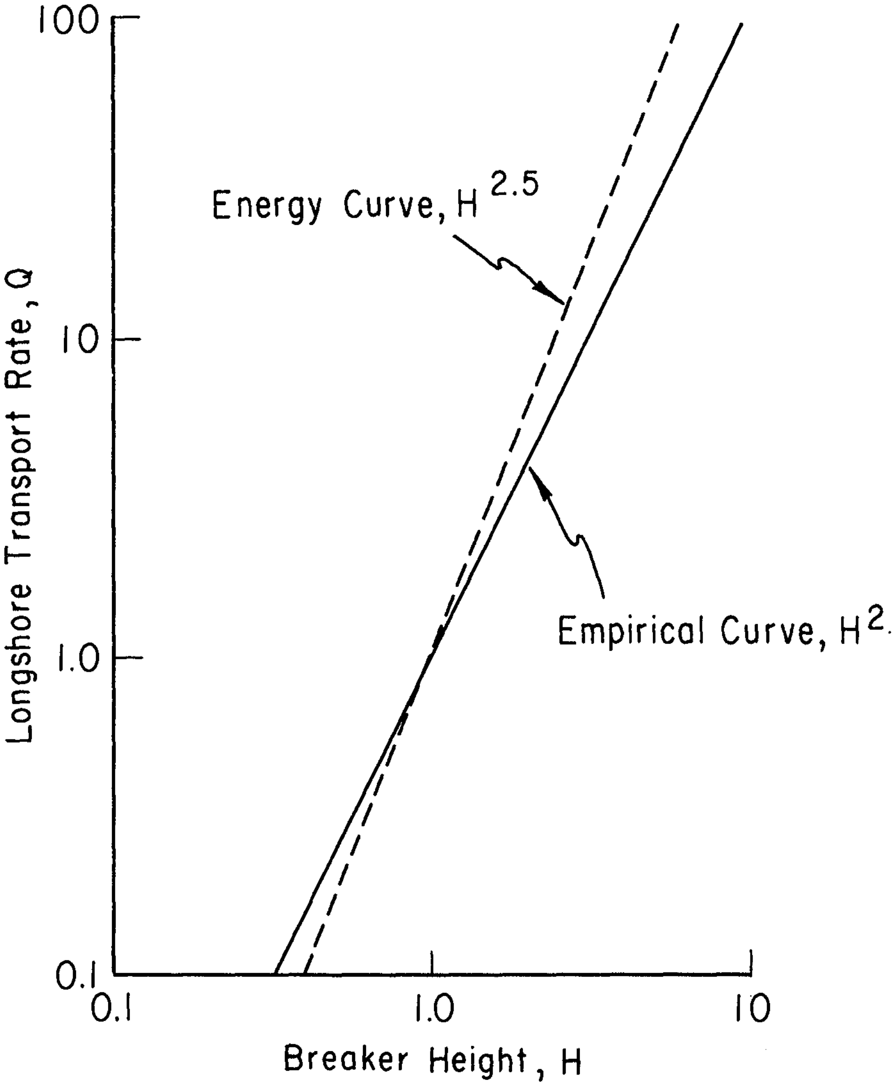
Continuity. However, another likely explanation is that equation (3) is a version of the conservation of mass, or continuity equation,

$$Q = D\ c\ V\ A \tag{5}$$

where c is a mean sediment concentration in the surf zone, V is a mean longshore current velocity, and A is the cross sectional area of the surf zone. D is a factor added to keep the units correct. If Q is 10^5 yd^3/yr and V and A are ft/sec and ft^2, then D = 11.68 (sec-yd^3/yr - ft^3).

In the following paragraphs, it is shown by plausibility arguments how equation (5) can be worked into a form like that of equation (3). In order to do this, it is necessary to have relations for c, V, and A. Since there does not appear to be any way of predicting concentration in the surf zone, c will be obtained from measurements (Watts, 1953a; Fairchild, unpublished). It is then necessary to obtain relations for the longshore current velocity, V, and the cross sectional area, A.

There are many equations available which purport to predict the mean longshore current velocity, V, but it has been shown that only two of them agree with both the best field and the best laboratory data (Galvin, 1967). One of these two equations, developed from elementary continuity considerations (Galvin and Eagleson, 1965), is



HEIGHT DEPENDENCE OF ENERGY AND EMPIRICAL CURVES
Figure 4

$$V = g\ m\ T\ \sin\ 2\theta_b \qquad (6)$$

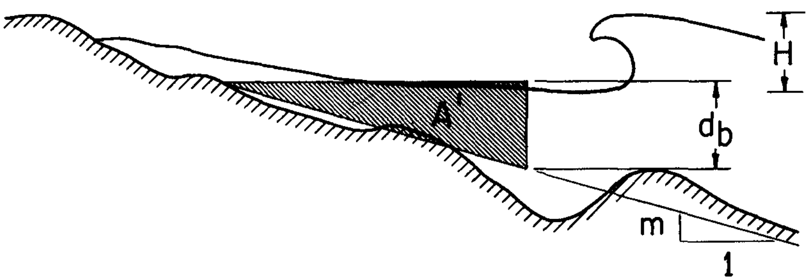
where g = acceleration of gravity; m = beach slope as defined in Figure 5; T = wave period; and θ_b = the angle between the wave crest at breaking and the shoreline. Since equation (3) attempts to predict gross transport rates, direction does not matter, and the sign of angle θ_b in (6) can be ignored.

For mean cross-sectional area, A, the surf zone will be approximated by a triangle bounded on the seaward side by a depth equal to βH, where β is the breaker depth-to-height ratio for the given slope, as shown in Figure 5. The area, A', of the triangle for a given wave height is thus

$$A' = (\beta H)^2/(2m) \qquad (7)$$

which is how H^2 gets into equation (5). The area A' is somewhat less than the true area of the surf zone (Figure 5). Since (7) refers to A' for a specific wave condition, it is necessary to convert this to the annual mean area (A) for use in equation (5), by a factor K, where

$$K = \frac{\text{annual mean of individual } H^2}{\text{square of annual mean}} \qquad (8)$$



AREA OF SURF ZONE

Figure 5

Thus, the average annual area is

$$A = K\ (\beta H)^2/(2m) \tag{9}$$

Putting equations (6) and (9) into (5) results in (10)

$$Q = D\ K\ g\ \beta^2 c\ T\ H^2\ \sin\ \theta_b \tag{10}$$

assuming that $\sin\ 2\theta_b = 2\ \sin\ \theta_b$ for the small angles involved. Note that the slope, m, present in both velocity (6) and area (9), has cancelled out of the equation for transport rate (10).

Check on Continuity Hypothesis. If equation (10) is an explanation of the empirically derived equation (3), then the factors on the right side of (10), exclusive of H^2, should be equivalent to or less than the factor 2 on the right hand side of equation (3). That is,

$$D\ K\ g\ \beta^2\ c\ T\ \sin\ \theta_b \leq 2 \tag{11}$$

where the ≤ enters because the curve on Figure 3 is an envelope above almost all known values, and because A was derived as a minimum value. It is now of interest to see whether reasonable values of K, β, c, T, and θ_b will satisfy (11).

Data for concentration are adopted from Watts (1953a) and Fairchild (unpublished) according to the following calculation:

$$c = c_w \gamma_{sw}/(\gamma_q(1-\varepsilon)) \tag{12}$$

where c is the concentration given in (5), c_w is the concentration by weight given by Watts (1953a); $\gamma_{sw} = 64\ \text{lbs/ft}^3$; $\gamma_q = 62.4 \times 2.65 = 165.4\ \text{lbs/ft}^3$; and ε is the ratio (voids in beach sand)/(voids + solids in sand) assumed to equal 0.4. With these substitutions, equation (12) becomes

$$c = 0.65\ c_w \tag{13}$$

From Watts' paper, an average value of c_w is about 0.5×10^{-3}, so that $c = 0.32 \times 10^{-3}$, a concentration which includes allowance for void space. Fairchild's data average around 0.46×10^{-3}.

The value of β is taken to be 1.3, a value traditionally used by engineers and one which has some experimental and theoretical basis (Iversen, 1952). Values of K have been obtained from calculation of equation (8) using visually estimated breaker heights from the COSOP data. Wave period T is also taken from the COSOP data. The value of θ_b is assumed to be 8^o, which is a mean of three field studies tabulated by Galvin and Nelson (1967) and which also is a representative mean value for data obtained in the CERC Beach Evaluation Program.

Tests of equation (11) for five coastal localities are shown in Table 2, where ( ) is used as a symbol for the left side of equation (11). The data in Table 2 show that ( ) is indeed less than 2, averaging about 0.50. While this is not compelling evidence in favor of the continuity hypothesis, these data do suggest that the hypothesis is worth further examination.

Table 2. CHECK ON CONTINUITY HYPOTHESIS

Locality	K -	T sec	c vol/vol	( )* -	( )/2 -
Short Beach, N.Y.	1.5	6.8	0.00046	0.42	0.21
Monmouth Beach, N.J.	1.4	6.4	0.00046	0.36	0.18
Hillsboro Inlet, Fla.	2.2	5.8	0.00046	0.52	0.26
Cape San Blas, Fla.	3.4	5.5	0.00046	0.76	0.38
Yaquina Bay, Ore.	1.3	13.0	0.00032	0.48	0.24

*( ) = $Dg\beta^2KcT \sin \theta_b$ as in equation (11)

where $D = 11.68$ sec-yd^3/yr-ft^3

$g = 32.2$ ft/sec^2

$\beta = 1.3$

$\theta_b = 8^o$

Assumptions of Continuity Hypothesis. The following paragraphs discuss the principal assumptions underlying the continuity hypothesis. Ad hoc reasons for favoring a continuity approach to surf zone motion have been previously advanced (Galvin, 1967, p. 299-300).

Assumption 1. The passage of waves through the littoral zone initiates sediment motion, so that this sediment may be moved alongshore even by weak longshore currents. Explicit statements of this assumption are given by the Beach Erosion Board (1933, paragraph 5/7), Kalkanis (1964, p.2), and Caldwell (1966, p. 146), and it seems well verified by observation.

Assumption 2. Longshore transport of littoral drift is accomplished principally as suspended load transport. There are some field and laboratory data which support this assumption. On the basis of his field measurements, Watts (1953a, p. 41) concludes that "the total suspended material movement can be an important factor in a littoral drift analysis". The data of Thornton (1969, Appendix B), based on measurement of transport rates with bedload traps, yield transport rates between a tenth and a hundredth of the value that would be expected from the longshore transport rate-energy flux correlation on

Figure 1 (M. M. Das, personal communication, 1970). If the traps were functioning properly, and if order-of-magnitude faith in Figure 1 is justified, then Thornton's data indicate that bedload is less important than suspended load in longshore transport. Saville (1950, p. 564) concludes, on the basis of his laboratory experiments, that "On equilibrium storm beaches, the sediment transportation was produced mainly by the movement of material in suspension by the littoral current." On the other hand, Komar (1969, p. 54) suggests that "suspended load transport of sand in the surf zone is less important than bedload transport" since his measurements appear to be explained by a bedload theory (Komar and Inman, 1970, p. 5921).

Assumption 3. Suspended sediment concentration in the surf zone can be approximated by a single average value. Watts (1953a, p. 40) states that there is some evidence for a uniform concentration across much of the surf zone, but there is little data available on this point.

Assumption 4. The mean longshore current velocity is given by equation (5). Comparison with data shows that this equation is one of two that fit the best data, it resembles the equation of Longuet-Higgins (1970, p. 6784), and it is consistent with the continuity hypothesis in that it was derived from continuity assumptions also (Galvin, 1967).

CONCLUSIONS

1. Gross longshore transport rates obtained from long-term field measurements are correlated with mean breaker height (Figure 3) by the empirical relation, $Q = 2H^2$, where Q is in 10^5 yd^3/yr and H is in feet (if measured in 10^5 m^3/yr and meters, the empirical relation becomes $Q = 16.5H^2$).

2. The empirical relation is conservative in predicting gross longshore transport rates now known (1970). Seven of 11 gross longshore transport rates from long-term field measurements are between 75 and 100% of their respective $2H^2$ values, and only one of the 11 rates is numerically greater than $2H^2$ (Figure 3).

3. All known net longshore transport rates which differ significantly from the gross rates have measured Q values that are numerically less than $2H^2$. In other words, the empirical relation approximately predicts the gross longshore transport rates and forms an envelope above the net longshore transport rates.

4. A physical explanation of $Q= 2H^2$, supported by some data from published studies, suggests that littoral drift is moved primarily as suspended load during longshore transport.

5. The physical explanation assumes conservation of suspended sediment in a longshore current whose mean velocity is given by equation (6) and whose cross-sectional area is a triangle having the breaker depth as its seaward side (Figure 5). The resulting expression (10) for Q is independent of beach slope and consistent with the limited field data available (Table 2).

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