CHAPTER 48

LITTORAL TRANSPORT AND ENERGY RELATIONSHIPS

L Bajorunas
National Oceanic and Atmospheric Administration
Detroit, Michigan 48226

The littoral transport rates in the Great Lakes were obtained two distinctly different ways, long-term averages from drift accumulations and hourly averages were measured in the St Clair River which receives sand from Lake Huron beaches Statistical analysis of both the recorded energy elements and measured sediment transport rates indicates that a combination of energy elements and environmental factors consisting of wave power and duration, current speed, and length of shoreline produces the best correlation with the transport rate Dimensional analysis expands the process-response model by including sediment-size and specific-weight parameters

INTRODUCTION

The St Clair River, which emerges from Lake Huron, carries little sediment during calm lake conditions, however, during storms, it transports significant amounts of sediment from Lake Huron beaches adjoining the river Extensive measurements were made during the spring and fall of 1965 to determine the amount and characteristics of the sediment transported both in suspension and as bedload by the St Clair River Simultaneous recordings were made of the energy elements in Lake Huron that could contribute to the pickup of sediment from the beaches and transportation downdrift into the St Clair River

SEDIMENT TRANSPORT

Measurement methods

The St Clair River heads at the southern end of Lake Huron (Fig 1) where it passes through a restricted and narrow reach, "The St Clair Rapids", with water velocities up to 2 m/s and associated extreme turbulence Exposure to lake waves and very heavy vessel traffic prohibited the use of this reach and, therefore, a river cross-section further downstream was selected for measurement of sediment transport Insignificant deposition has been observed in the reach of the river between the lake and the metering section, which is at the shoal just downstream of the first river bend and some boat slips

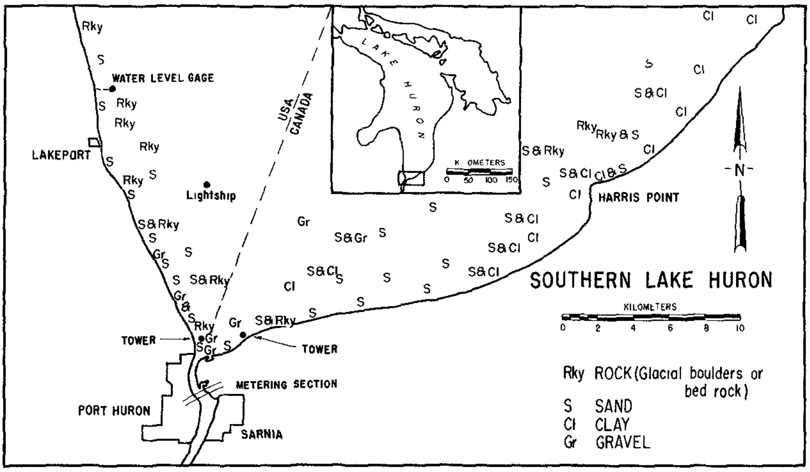

Fig 1 Southern Lake Huron

The river cross-section was divided into eight panels for the purpose of sediment measurement Water samples were taken and current velocities recorded at 0 1 depth intervals at the mid-vertical of each panel A second water sampler, simultaneously took samples at a constant 0 4 depth Each vertical was sampled twenty times, and the complete river crossing produced at least 160 samples U S P-61 suspended sediment samplers and Price current meters were used in the data collection program The sand moving within five centimeters of the river bottom was trapped in an Arnhem bedload sampler The time required for sampling one panel, including the time for positioning of the survey boat, was about one hour It would have been possible to complete a river crossing in a day but weather and heavy vessel traffic caused unexpected delays and on only one occasion was a river crossing completed in a single day

Transport rates

The measured concentration of suspended sediment by weight ranged from 0 3 to 90 ppm, with an average of about 10 ppm The sediment transport in suspension was determined using the standard method of the current velocity times the cross-sectional area times the suspended sediment concentration An average density of 1700 kg/m^3 was used to change the suspended sediment transport rate by weight into rate by volume Repeated sampling at the 0 4 depth shows that the concentration is subject to considerable variation with time In addition to the seemingly random variation some regular pulsation in sediment concentration was observed, which in no way can be related with the flow in the St Clair River

The bedload was determined by extrapolating the measured rate in the sampler to represent the transport over the panel width Sediment movement along the river bed amounted to a fraction of one percent of the suspended sediment and was not considered further The measured rates of suspended and bedload sediment are given in Table 1 Table 1 also lists the sum of the measured values and the estimated total transport in the river In two cases the measurements were insufficient for a reasonable estimate Comparison of the measured portion of the transport with the estimated total gives some indication of the magnitude of errors

TABLE 1 SUSPENDED AND BEDLOAD SEDIMENT IN ST CLAIR RIVER

Date 1965	*River panels 1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*Sum of meas*	*Estim total trans*
				SUSPENDED SEDIMENT m^3/hr						
14 May	9 2	18 5	14 6	6 2	10 8	8 5*	6 2*	3 0*	59 3	77
17 "	4 1	6 6	5 3	7 3	--	--	--	--	23 3	34
19 "	6 6	12 5	9 2	15 2	9 3	5 9	5 3	2 0	66 0	66
20 "	6 4	8 7	10 9	--	--	--	--	--	26 0	48
21 "	2 7	7 5	13 3	12 9	--	--	--	--	36 4	54
3 Jun	8 9	13 9	10 2	9 2	--	--	--	--	42 2	62
4 "	--	--	--	--	6 8	7 7	5 3	1 9	21 7	68
14 "	22 6	35 6	--	--	--	--	--	--	58 2	160
15 "	15 4*	26 4*	24 2	11 0	12 1	9 9	7 7	3 3	68 2	110
16 "	10 4	16 2	16 4	10 7	--	--	--	--	53 7	79
3 Nov	3 2	--	--	--	--	--	--	--	3 2	--
4 "	22 9	41 5	28 4	37 7	--	--	--	--	130 5	190
6 "	--	--	--	--	10 9	4 1	6 6	3 4	25 0	78
9 "	30 6	46 8	27 0	19 8	19 8	18 0	12 6*	5 4*	162 0	180
10 "	--	--	--	--	--	--	3 6	1 7	5 3	--
18 "	40 5	64 0	46 4	48 6	37 5	--	--	--	237 0	300
19 "	--	--	--	--	--	9 5	8 9	4 4	22 8	110
				BEDLOAD SEDIMENT, $10^{-3} m^3/hr$						
19 May	9	10	9	15	9	9	9	6	76	
8 Nov	2	5	7	16	5	14	4	3	56	

**estimated*

Sediment Characteristics

A detailed description of the sediments in St Clair River was published by Duane (1967) and, therefore, only a summary is given here The suspended sediment is mostly of the fine sand size, ranging from 0 11 mm to 0 17 mm, with a few particles reaching 1 0 mm size Material is dominantly quartz although other minerals and organic matter are present The bedload sediment size ranges from 0 25 mm to 2 6 mm

Samples from Lake Huron beaches show the same composition and grain-size characteristics as the suspended load and bedload of the St Clair River Areal extent of sand along lower Lake Huron is depicted in Fig 1 Mandelbaum (1966) reported that sediment in the St Clair River delta at the entrance to Lake St Clair contains some finer grain sizes than those measured in the river

ENERGY ELEMENTS

Elements measured

In addition to the primary variables, wind speed and direction, wave height and period, and current speed and direction, some elements probably only remotely related to the study were recorded, such as barometric pressure, and air and water temperature Lake level and river discharge data were available from continuous data collection programs on the lakes Instrumentation was placed at five locations (see Fig 1) on the Coast Guard Light Ship, on two specially erected towers, and on two submerged tripods Towers, as described by Duane and Saylor (1966) were placed near the east and west shores in 5 7 m and 6 6 m depths, respectively Submerged tripods were located between the shore and the towers in 1 5 m depth and supported current meters only Data pertinent to the sediment sampling periods are listed in Table 2

TABLE 2 MEASURED ENERGY ELEMENTS

Date 1965	Lake level m	Wind Speed m/s	Wind Dir	Wind Persist hr	East Shore Wave Height cm	East Shore Wave Per s	East Shore Curr Speed cm/s	West Shore Wave Height cm	West Shore Wave Per s	West Shore Curr Speed cm/s
14 May	175 68	3 3	NE	4	--	--	--	6	3 0	16
17 "	175 77	4 2	W	10	18	3 3	10*	11	3 4	17
19 "	175 76	4 0	N	8	25	3 0	11	17	3 2	20
20 "	175 77	4 3	N	13	--	--	9	12	3 1	18
21 "	175 71	4 2	SE	4	--	--	9	6	3 4	17
3 Jun	175 80	5 5	N	9	40	3 1	9	36	3 2	12
4 "	175 77	3 9	N	6	12	3 0	9	--	--	14
14 "	175 84	7 6	N	34	61	4 2	15*	37	3 6	20*
15 "	175 82	8 8	N	5	77	3 6	18	37	3 5	24
16 "	175 83	7 5	N	3	60	3 2	15*	29	3 2	15
4 Nov	176 02	5 6	N	11	64	7 5	27	53	4 1	15*
6 "	175 86	3 8	S	25	8	3 7	3	--	--	21
9 "	175 92	4 3	NW	22	41	5 2	40	46	4 5	10
18 "	175 92	5 3	W	42	31	6 2	110	--	--	--
19 "	175 89	1 8	W	15	29	5 4	10	--	--	--

Recorded current direction on the listed days was towards the St Clair River despite the variable winds

**estimated*

Overwater wind was recorded at the two towers and at the Light Ship The wind over this rather small area was quite uniform The data listed were obtained from the tower near the west shore Wind persistence was defined as the period of time prior to sediment sampling having essentially the same wind speed and direction as that recorded during the sediment sampling period All higher wind speeds, lower speeds of less than one hour duration, and deviations of less than 45° in direction were included in the determination of persistence

Waves were also recorded at the two towers and near the Light Ship The wave gage near the Light Ship was difficult to maintain due mainly to excessive cable length The data recorded at this location were insufficient for analysis Wave recordings taken at the two tower locations were more successful, but even in these locations some records were missing, as was the case on 18 November when the highest sediment movement was measured Heights listed in Table 2 are of significant waves, which are defined as four times the standard deviation of the wave gage record The linear average values read from wave spectra curves produced by the Coastal Engineering Research Center were multiplied by a factor of 2 7 to obtain significant waves The 2 7 factor was derived from data by Cole (1967) The wave periods are those at which maximum energy was produced Analyses of several 20 minute wave records taken at different times during the sediment sampling period were averaged to obtain the listed values No attempt was made to estimate the missing waves from wind records Cole concluded on the basis of carefully recorded wind and wave data that existing wind and wave relationships were producing marginal results

Currents were recorded at four locations One current sensor was attached to each tower and the other two sensors were placed on the two tripods The propeller type current sensors were placed in a tube about 10 cm above the bottom These so-called ducted current meters were responsive to currents along the axis of the tube, which was oriented parallel to the shoreline The direction indicator was freely suspended and assumed the direction of dominant current Current speed and direction were both recorded, however, Table 2 lists only current speeds recorded on the tripods The currents at the times listed were always toward to the head of the river The meters frequently jammed during operation due to sand particles or weeds lodging between tube and propeller Some missing current data were estimated with reasonable accuracy either from the records immediately preceding or following the missing records or from the currents recorded on the towers The estimated values are so indicated

Lake Huron levels and outflows are recorded by the U S Lake Survey Levels are recorded by five water-level gages, with those recorded at the Lakeport gage listed In addition to the long-term gradual change of lake levels caused by the changing water volume there are frequently quite large local water level changes caused by wind and barometric pressure In contrast with the oceans, lunar tides in the Great Lakes are quite small, not exceeding 15 cm During the sediment sampling periods, however, only insignificant short-term changes in lake level were recorded The flow in the St Clair River has a small day-to-day variation and was gradually increasing from 4700 m^3/s in May, to 4900 m^3/s in June, and to 5200 m^3/s in November

ANALYSIS OF TRANSPORT FACTORS

Littoral transport is affected by numerous factors basically related to the sediment supply and characteristics, and energy in its various forms A brief discussion of the more obvious factors and their numerical evaluation follows

Sediment Characteristics

Recent investigations utilizing both models and the natural environment point to the important effect the sediment size distribution has on the movement rate in littoral environments However, no agreement exists on magnitude of that effect A comprehensive study of sediment movement in the ocean environment was made by Ingle (1966) He found that sediment transport doubles with the change in sediment size from 0 14 mm to 0 20 mm, and increases by 20% for the change from 0 20 mm to 0 28 mm Model studies by Larras (1966) indicate that the maximum transport takes place when the median diameter of the sediment is 0 9 mm Material finer or coarser than this moves at significantly lower rates For example, fine sand of the size on Lake Huron beaches moves at one third the rate of the 0 9 mm size sediment Contrary findings are reported by Iwagaki and Sawaragi [Homma, (1966)] Their equation indicates that sediment movement decreases with increase of the square root of sediment diameter In present study the dimensional analysis, discussed later, indicates that transport increases with the square root of sediment size This is in general agreement with findings by others for the fine to medium sand

Sediment must be freely available along the shoreline for equilibrium to exist between energy and the volume of sediment in movement In the study area, sand on the east shore extends northeastward for about 20 km and ends before Harris Point The areal extent of sand on the west shore cannot be clearly assessed, although it is estimated to be in the order of 20 km Sediment movement in this location is somewhat retarded by scattered rocks of glacial origin

Effective Shoreline and Wave Duration

Two limiting factors in sediment transport must be considered the length of unobstructed shoreline and the duration of wave action The wave duration is the limiting factor for very long shorelines, however, long shorelines without either natural or man-made barriers to sediment movement rarely exist More frequently the length of unobstructed shorelines sets the limit to sediment transport This phenomenon in nature, however, is rather complex due to the continuous variation of both the energy elements during a storm and the sediment characteristics along a shoreline Statistical methods must therefore be applied when considering observations in nature The effect of shoreline length was investigated by Bajorunas (1961) based on long-term drift accumulation on the updrift side of harbors or natural barriers Present investigations consider a variable duration of wave action over a given length of shoreline Persistence of wind speed and direction is used here as an index of the duration of waves

Effective Shoreline in the 1961 study varied from 2 to 67 km with the wave duration undetermined Since sediment data was obtained from accumulations extending over long periods, sometimes exceeding 90 years, it seems that any reasonable wave duration could be applicable and that the transport is, therefore, limited by the effective shoreline rather than by wave duration It is difficult to isolate the effect of the shoreline in the empirical littoral transport and energy equation derived in 1961 It was therefore necessary to replace that equation

$$Q = 19\ E_o \sin \alpha_o \ (1 - e^{-0\ 023 S \cot \alpha_o}) \qquad (1)$$

by the theoretically less desirable

$$Q = 4\ 5\ E_o \sin 2\alpha_o (1 - e^{-0\ 04S}) \qquad (2)$$

where Q is the annual littoral transport, cubic yards in equation (1) and m^3 in (2)

E_o is the annual deepwater wave energy, millions of foot-pounds in equation (1) and 10^6 joules in (2)

S is the effective length of shoreline, miles in (1) and km in (2)

α_o is the angle between the shoreline and the wave crest

Fig 2 contains the 1961 data which depicts transport per energy unit versus the effective shoreline

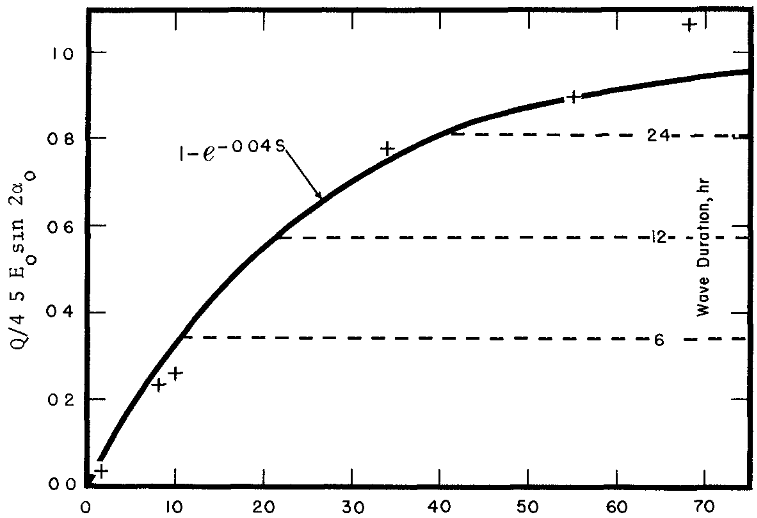

Fig 2 Effect of shoreline on littoral transport

Wave Duration in the present study was based on recorded wind persistence and varied from 3 to 34 hours while the effective shoreline was about 20 km Data in Fig 3 indicate that the wave duration is a significant factor in sediment transport if less than about twelve hours The effective shoreline becomes the determining factor for longer periods and on these occasions the transport per energy unit remains more or less constant The effect of wave duration was expressed mathematically as $(1 - e^{-0\ 07D})$ based on meager field data and on the assumption that it must have an exponential form similar to that derived for effective shoreline

The dependence of drift rates upon both the wave duration and effective shoreline requires selection and use of that factor which restricts the transport more

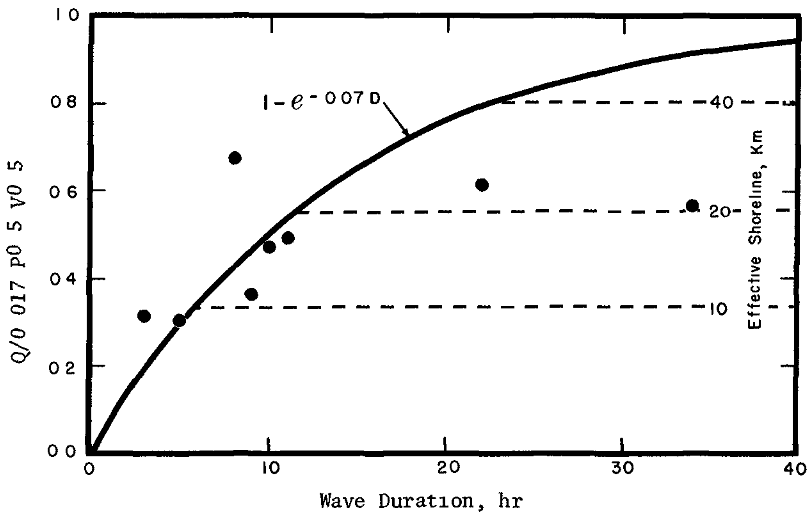

Fig 3 Effect of wave duration on littoral transport

Energy Elements

Wave power, as used here, was derived from wave energy and wave frequency The wave energy per unit width of wave crest is expressed as

$$E = 0\ 125\ \gamma H^2 L \tag{4}$$

where γ is specific weight of water
H is wave height
L is wave length

Considering the rather small waves in this particular case, the correction for wave shape was deleted and the wave length was expressed by $gT^2/2\pi$, where T indicates wave period The energy transmitted to the shore by wave train in a time period t is equal to $E_t = nET^{-1}t$, where n is the ratio of wave group velocity to the phase velocity and is, in this case, approximately 0 5 The wave energy exerted over a time period t is thus

$$E_t = (32\pi)^{-1}\gamma\ g\ H^2\ T\ t \qquad (5)$$

The above equation is correct for any unit system The equation can further be simplified to $E_t = 960\ H^2\ Tt$, if the international system (SI) is used where the wave energy is expressed in joules To conform with the sediment transport, t = 3600 s was used here Wave frequency, if considered as an independent factor, greatly improves the correlation between sediment transport and energy elements The combination of wave energy and wave frequency results in wave power (P = Ef), where the wave height is the only significant element This would indicate that the wave height and not the wave length or wave period has an effect on the transport rate

Currents It becomes obvious from the analysis of the data collected, that wave energy alone or in combination with the angle of wave approach is not sufficient to define the movement of material In this particular location, morever, with its prevailing winds from the west and currents from the east, the results would be erroneous When the waves and currents come from differing directions the sediment saltation is necessarily complex, however, net movement in the study area was always in the direction of the currents One can speculate then that waves lift the material and the currents transport it in the direction of flow Previous observations of shoaling in a harbor also indicate that sediment moves in the direction of currents [Bajorunas and Duane, (1967)]

Investigations of lake currents by Saylor (1966) indicate that currents generated by winds reach equilibrium with the wind at about 0 033 of the wind speed This occurs in a rather short period of one to three hours Currents persist for days after wind cessation, and therefore have quite stable patterns in geographic locations where certain winds prevail, such as the Great Lakes with their predominantly westerly winds Currents in the open lake flow 10-15 degrees to the right of the wind direction with current speed and direction practically independent of surface wave activity Currents in nearshore locations are modified by shoreline configuration and, depending on that configuration, might flow against the wind Occurrences of this type were recorded frequently in the study area The data establishes a strong relationship between the volume of sediment being transported and the current speed There is no apparent upper limit for this relationship

RELATIONSHIPS

Logarithmic plotting (not shown) of the rate of sediment transport, adjusted for effective shoreline and wave duration, against a factor consisting of a combination of wave power and current speed indicates that transport is directly related to the square root of this factor and the relationship can be expressed as follows if f(S,D) denotes the limiting effects either of the shoreline or the wave duration.

$$Q = 0.39x(P\,v)^{0.5} f(S,D) \tag{6}$$

where x represents the unknown dimensions of the numerical factor. Analysis indicates that sediment characteristics, expressed by sediment size d and by specific weight of sediment in water $g(\rho-1)$, will satisfy the dimensional requirements. Average values of the sediment in the study area, $d = 0.14$ mm, and $\rho = 2.4$ g cm^{-3}, allow us to determine the numerical value of x. Thus, the equation (6) becomes

$$Q = 3.9\,[P\,v\,d\,(\rho-1)^{-1}\,g^{-1}]^{0.5} f(S,D) \tag{7}$$

where Q is littoral transport, m^3/hr
3.9 is constant, dimensionless factor
P is wave power, J/s, computed as hourly wave energy times wave frequency
v is nearshore current speed, m/s
d is average sediment size, mm, fine to medium sand sizes only
ρ is sediment density, g cm^{-3}
g is acceleration due to gravity, ms^{-2}
f(S,D) is the lower value of either $(1-e^{-0.04S})$ or $(1-e^{-0.07D})$ where S is effective shoreline, km, and D is duration of waves, hr.

Fig. 4 provides a comparison of the measured transport with that computed by equations (2) and (7).

SUMMARY

The littoral transport rates in the Great Lakes were obtained two distinctly different ways. The long-term averages were derived from drift accumulations over periods sometimes exceeding 90 years on the updrift side of harbors or natural barriers. The hourly averages were directly measured in the St. Clair River into which sediment moves from Lake Huron beaches. At the same time sediment characteristics were determined and recordings of the energy elements analyzed to relate them with the measured sediment transport rates.

Analysis of data indicates that:

1. Wave power and nearshore currents are the main elements in sediment movement. On occasions when the current is flowing counter to the waves, sediment moves with the current. One can speculate that waves are lifting material and the current is transporting it in the direction of flow. Transport rate is directly related to the square root of wave power and current speed.

2. Length of sediment-contributing shoreline, exposed to waves and currents, is a significant factor in determining the transport rate. Analysis of data on shorelines varying from 2 to 67 km in length indicates that transport grows exponentially with the shoreline length towards a steady-state value.

3. History of acting elements, as expressed by wave duration,

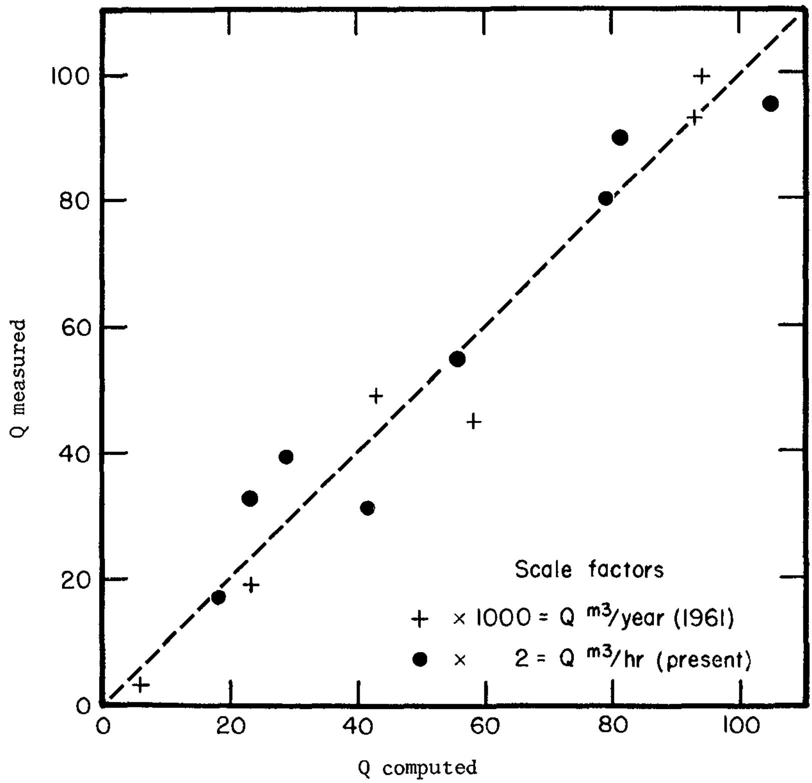

Fig 4 Comparison of measured littoral transport with computed

helps to explain the transport growth and is a limiting factor in cases of short wave duration on a long shoreline Wave duration, which varied from 3 to 34 hours, has a similar effect to that of shoreline length, the effect increases exponentially with the increase in duration towards a steady-state value

4 Transport increases with the square root of sediment size This conclusion was reached indirectly by dimensional analysis and generally agrees with observations in oceans and models for the fine and medium sand size

5 Equations utilizing wave energy, angle of wave approach, and shoreline length could provide reasonable estimate of sediment movement on an open shoreline along which the wind, waves, and current progress in the same direction They would fail, however, in the complex wave and current environment, in such environment the nearshore current speed and direction is an essential factor

ACKNOWLEDGEMENTS

The field collection of data, laboratory procedures, and analysis were carried out in connection with the general research program of the Great Lakes Research Center, U S Lake Survey, Army Corps of Engineers Permission granted by the Chief of Engineers to publish this information is appreciated Fieldwork was directed by Dr D B Duane, presently with the U S Army Coastal Engineering Research Center Essential assistance was provided by Mr W P Ward in analysis of the sediment data and Mr P C Liu in wave energy calculations

REFERENCES

Bajorunas, L (1961) Littoral transport in the Great Lakes, Proc 7th Coastal Eng Conf , Council on Wave Res , Univ Calif , Berkeley, 326-341

Bajorunas, L and Duane, D B (1967) Offshore bars and harbor shoaling, J Geophys, Res , 72, 6195-6205

Cole, A L (1967) An evaluation of wind analysis and wave hindcasting methods as applied to the Great Lakes, Proc Tenth Conf Great Lakes Res , Intern Asso for Great Lakes Res , Ann Arbor, Mich , 186-196

Duane, D (1967) Characteristics of the sediment load in the St Clair River, Proc Tenth Conf Great Lakes Res , Intern Asso for Great Lakes Res , Ann Arbor, Mich , 115-132

Duane, D B , and Saylor, J H (1966) Portable Great Lakes research towers, Proc Ninth Conf Great Lakes Res , Intern Asso for Great Lakes Res , Ann Arbor, Mich , 295-300

Homma, M (1966) Coastal sediment studies in Japan, Univ of Tokyo, 11 p

Ingle, J C (1966) The movement of Beach Sand, Univ of S Calif 221 p

Larras, J (1966) Cubes de sable charries par la houle parallelement a la cote, Anales des Ponts at Chaussees, Paris, 71-76

Mandelbaum, H (1966) Sedimentation in the St Clair River delta, Proc Ninth Conf Great Lakes Res , Univ of Michigan, Ann Arbor, 192-202

Saylor, J H (1966) Modification of nearshore currents by coastal structures, Misc paper, Lake Survey District, Corps of Engineers, Detroit, Michigan, 14 p