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Annual Variation of Longshore Sediment Transport in a Dissipative, Multi-Bar Nearshore Zone

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Abstract

Numerous measurements imply that longshore sediment transport varies in temporal scales of not only seconds, minutes or even hours, but also days and months, up to years. Such situations stimulate one to analyse and estimate the rate and variability of longshore sediment transport in meso- and long-term time scales.

The present analysis evaluates the annual longshore sediment transport in the multibar surf zone. On the basis of field investigations and some assumptions, a simple relationship for the global daily longshore sediment transport as a function of mean wave height was derived. The mean wave height ($\overline{H}$) input can be estimated either by computations from daily wind parameters and cross-shore profile shape or directly by measurements.

The accuracy of estimation or prediction of daily longshore sediment transport by the proposed method depends on the degree of stationarity of wind field. Given rates and distributions of longshore sediment transport correspond to definite hydrologic-morphodynamic conditions of the coastal zone. The latter encompass the dominance of oblique approach of waves to the shore, multiple breaking of waves, a multi-bar, mildly sloped ($\beta \approx 1.5\%$) shore and grain characteristics ($D_{50} \approx 0.022$ cm, $\varrho_s \approx 2.65$ g/cm^3) etc.

The intensity of sediment movement resulting from the applied procedure can, in some cases, be underestimated with respect to the total real sediment transport rate. This results from the use of empirical relationships derived on the basis of tracer measurements of sediment movement. The bedload is mainly taken into account in such methods.

1. Introduction

Sediment movement in the sea is traditionally divided into longshore and on- offshore. The present considerations deal with the longshore transport. The sediment transported in the longshore direction is most often a basic factor determining the spatial changes of the shoreline and is a very important factor of generation and movement of multi-scale erosive-accumulative coastal forms.

The basic parameters of longshore sediment transport depend upon many factors such as waves, currents and sea bottom shape. In literature the main interest of researchers is focused on mutual local coupling of the factors mentioned for optimal prediction of instantaneous transport rate. Few works exist which analyse this phenomenon on larger scales, mainly temporal ones. Numerous measurements imply that basic results of longshore sediment motion are observed in temporal scales of not only seconds, minutes or even hours, but days and months, up to years.

Such situations stimulate one to analyse and estimate the rate and variability of longshore sediment transport in meso- and long-term time scales.

Taking advantage of periodic measurements of bottom sediment movement (Pruszak & Zeidler 1988, 1992), an attempt has been made to estimate the rate and variability of longshore sediment transport, in scales of months and the entire year (or several years). Bottom sediment transport research was carried out for years by means of radioisotopic tracers (Owczarczyk et al. 1991), under conditions typical for a dissipative multi-bar sea shore.

1987 was chosen because measurements and observations of different kinds were available for this period. It is obvious that field data are most valuable and reliable as they result from natural spatial-temporal scales which are not distorted by elimination or isolation of important parameters. Considering the time scale, is mainly of meso-term dimensions. Hence the basic temporal scale (time step) is that of a day.

Assuming the following sequence of physical events (phenomena) occurring in a coastal zone:

$$\begin{array}{ccccccccc}
 & & & & \text{longshore} & & \multicolumn{3}{c}{\text{global longshore}} \\
\text{wind} & & \text{waves} & & \text{current} & & \multicolumn{3}{c}{\text{sediment transport}} \\
 & & & & & & \text{unitary} & \times t & \text{in scale } t \\
(\overline{v_w}, \overline{\varphi}) & \rightarrow & (\overline{H}, T) & \rightarrow & \overline{V} & \rightarrow & q[\mathrm{m}^3/\mathrm{s}] & \rightarrow & Q\ [\mathrm{m}^3/\mathrm{t}] \\
 & & \updownarrow & & \updownarrow & & (\overline{H}, \overline{V}) & & (\overline{H}, \overline{V}) \\
 & & \multicolumn{3}{c}{\text{assumed bathymetry}} & & & & \\
 & & \multicolumn{3}{c}{\overline{h}(x, y)} & & & &
\end{array}$$

where: $\overline{v_w}$, $\overline{\varphi}$, $\overline{H}$, $\overline{V}$, $\overline{h}$ – mean values for assumed temporal scales (e.g. $t = 1$ day) – one finds out that meteorological conditions are the first element of the sequence while sediment transport is the last.

Within tracer direct measurements the movement of sediment has been determined in the units [m^3/s] or [kg/m $\cdot$ h] and it can represent the unit transport rate (q). However it results, as a matter of fact, from averaging over various assumed time periods (t), e.g. 1 day. Waves and currents have also been subject to such averaging. Multiplying the quantities of unit transport (q) by the time of averaging (e.g. 1 day) one can obtain mean (per day) amounts of sediment (Q) transported in this time.

Taking into account the real sequence, e.g. monthly or annual, of consecutive diurnal hydrological situations one finally obtains the distributions of longshore sediment transport in various temporal extents.

2. Survey Conditions, Data Base and Assumptions

2.1. Survey Site and General Hydrodynamic Conditions

Measurements were carried out at the Coastal Research Station at Lubiatowo, which is situated on a transient seashore segment about 80 km west of Gdańsk, Fig. 1. The shore in this region has characteristic features occurring in the southern part of the Baltic Sea: it is a dissipative multi-bar shore (3–4 bars) with a sediment diameter $D_{50} \approx 0.022$ cm and mean bottom slope of about $\beta \approx 1.5\%$.

In this region, the maximum significant waves ($H_s = 1.6\overline{H}$) appearing during severe storm attain a height of 2–2.5 m (maximum 3.5 m) and a period of $T \approx 7$ s at the seaward boundary of the surf zone. Waves are most often directed obliquely at an average angle $\alpha_o = 20$–$30°$ from west to east. Gradual energy loss takes place as a result of wave transformation. At a depth of $h = 2$–3 m, where most often the biggest wave energy dissipation occurs, the mean storm wave height attains $\overline{H} \approx 1$ m (maximum 1.5 m) and wave period is $T = 4$–5 s. In the close vicinity of the shoreline ($h \approx 1$ m), where significant sediment movement is observed, storm waves attain mean height $\overline{H} \approx 0.3$–0.5 m (maximum 0.6 m) and a period of 4–5 s.

In the analysed region currents are definitely of wave origin. During storms, $\overline{H} > 0.4$ m at a depth of $h \approx 2$–3 m, measurements at these depths imply (Szmytkiewicz & Skaja 1991), the existence of mean longshore currents of order of 0.3–0.5 m/s (maximum 0.6 m/s). Closer to the shore ($h \approx 1.0$–1.5 m) these currents can be bigger in the conditions mentioned while at depths $h < 3.0$ m the currents are much smaller. In the case of weaker waves, $\overline{H} \approx 0.2$–0.3 m, but not more than $\overline{H} \leq 0.4$ m at depths $h = 2$–3 m, mean longshore currents in this region most often oscillate between 0.10 and 0.25 m/s. On- and offshore currents, as observations and measurements imply, attain mean velocities of 0.1–0.2 m/s in stormy conditions and are of an offshore direction. During severe storms $\overline{H} \geq 1$ m offshore current velocities increase to about 0.3 m/s, mainly closer to the bottom.

2.2. Measurement Data

Wind parameters

The wind field resulting from turbulent motion of air masses is a basic factor generating lithodynamic phenomena in the sea. This field is described by a temporal and spatial variable vector characterized by speed (v_w) and direction (φ). Relating these quantities to the hydro- and lithodynamic phenomena generated in the sea such as waves, currents, sediment movement etc. one usually manages with mean parameters of wind ($\overline{v_w}, \overline{\varphi}$). Because of the way routine meteorological observations are carried out (3 times a day) and temporal dimension of analysed phenomenon with a big (multi-hour) inertia scale, the basic one-day temporal averaging step has been assumed.

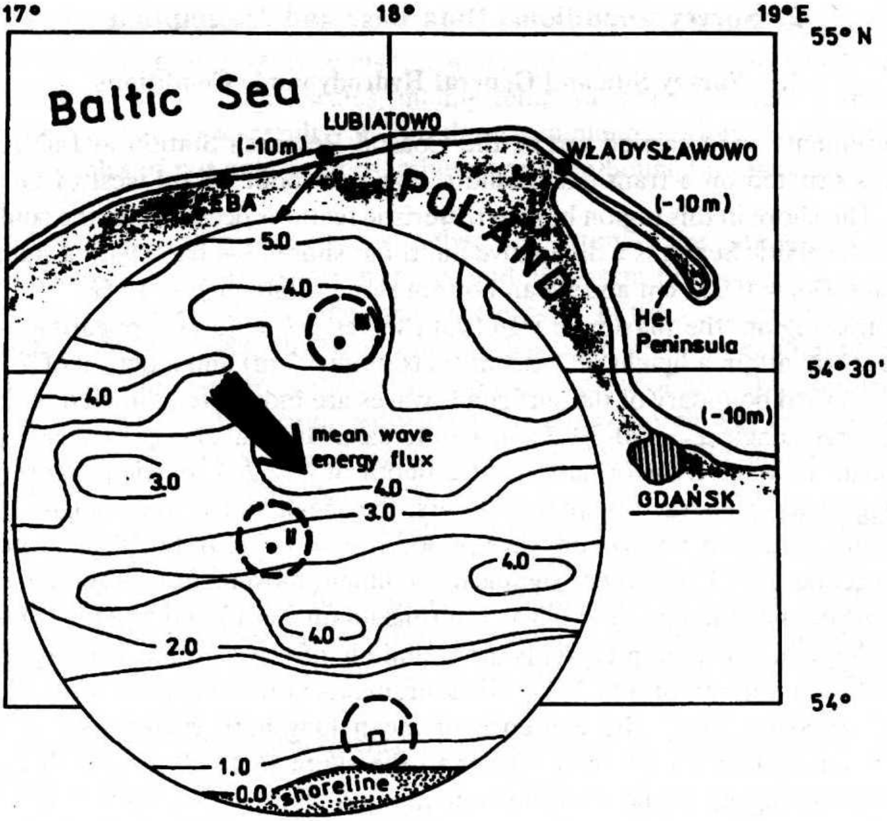

Fig. 1. Location and nearshore bathymetry of study area

The parameters of wind field ($\overline{v_w}, \overline{\varphi}$), assumed for further analysis, result from daily averaging of routine wind measurements carried out at the nearest permanent meteorological station at Łeba, about 12 km west of Lubiatowo, Fig. 1.

The degree of accordance between the average (daily) direction and wind speed in the region of survey and meteorological station at Łeba is given in Fig. 2. Although carried out for a short period (1–23.10.87) the comparison proves that the mean (daily) wind parameters at both Stations are similar.

Sediment movement

The measurements of various quantities describing bed load sediment transport were carried out for several years (1984–1989) in the region of the analysed shore segment at Lubiatowo. Within the research, simultaneous measurements of sediment movement in sea, wind, waves and currents were taken. Sediment movement, studied in the field with the use of a tracer method, covered various hydrodynamic situations and locations in the cross-shore profile. Despite their temporal and spatial limitations the measurements became a good basis for estimation and description of sediment transport in the surf zone and a number

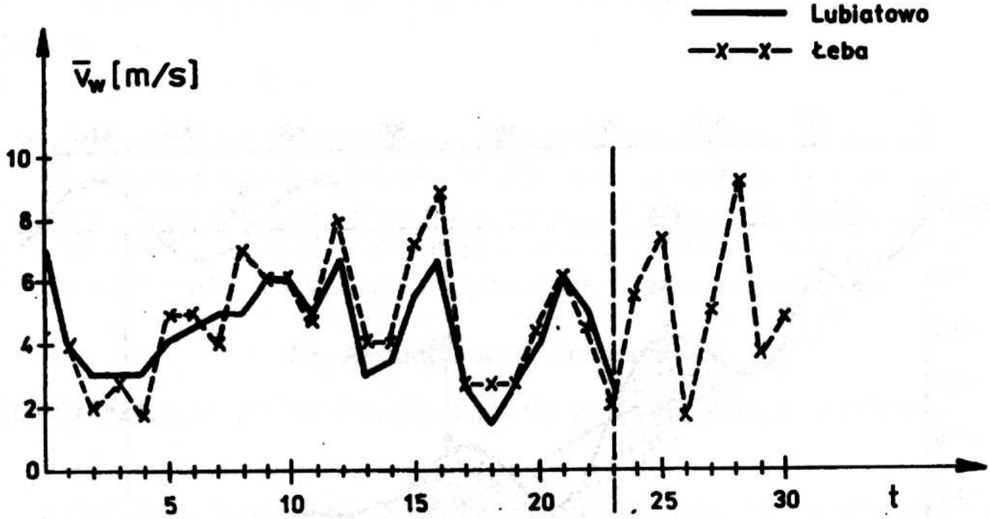

Fig. 2. Comparison of daily wind velocities at Lubiatowo and Meteorological Station in Łeba

of its important characteristics. Final results of some of these investigations are available in Pruszak & Zeidler (1988), (1992).

Even a rough analysis of measured data indicated the existence of continuous non-stationarity of processes studied, of temporal scale of hours (day). Such a non-stationarity results in the periods of intensive and small (or lack of) sediment transport following each other randomly according to wind-wave-current conditions. Thus one should manage the sequences of similar (after averaged) hydrodynamic situations distinguishing for example stormy conditions (A) corresponding to intensive sediment movement, moderate waves (B) and related moderate sediment movement and periods of minimum waves or stillness (C) i.e. a lack of sediment transport. A range of changes of unitary longshore sediment transport for variable depths of cross-shore profile and the functions of various parameters of waves and currents, for two basic wave-current situations (A) and (B) are given in Fig. 3.

The longshore transport rates depicted in Fig. 3, although given in [kg/m·h] units, result from multi-hour or multi-day times of averaging. Hence the temporal scale assumed previously to equal 1 day can approximately correspond in many cases to the mean period of averaging.

Assuming that the active part of a cross-shore profile most often reaches depths of 5–8 m, i.e. 500–800 m off shore and taking into account the equation:

$$q = q_i \ \Delta l_i \ (\Delta \varrho)^{-1} \ t^{-1} \quad [\mathrm{m}^3/\mathrm{s}] \tag{1}$$

where:

q_i – sediment transport in regions I, II, III,

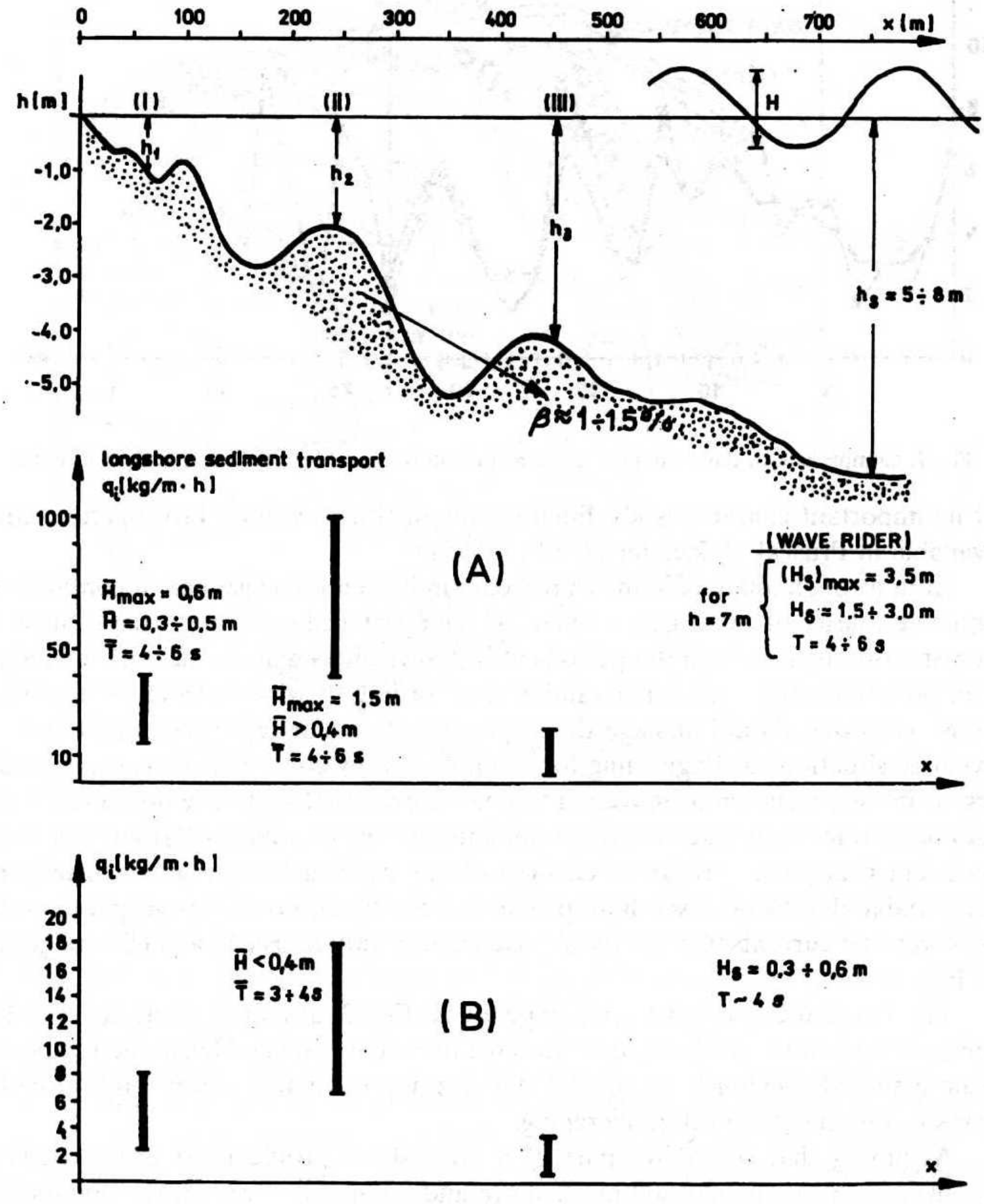

Fig. 3. Sand transport rate for variable depths of cross-shore profile

Δl_i – width of regions I, II, III ($i = 1 \ldots 3$) along cross-shore profile,

$\Delta\varrho = \varrho_s - \varrho$,

t – time ($t = 3600$ s)

– one can obtain the global longshore transport rate inside the active zone.

Our studies (Pruszak & Zeidler 1992) have shown that during storms (A) the longshore transport global unit q in the entire surf zone varies most often in the 1.95–6.0 $\times 10^{-3}$ m^3/s range and in the situation of moderate waves (B) from 0.35 to 1.95 $\times 10^{-3}$ m^3/s, likely to attain higher rates in extreme conditions.

2.3. Assumptions of Computations

Survey conditions and the data file imply the following basis assumptions:

- natural, mildly sloped and sandy shore;
- daily homogeneous wind field resulting from averaging of measurements taken three times a day;
- similarity of wind field parameters at Łeba and Lubiatowo;
- distinction and assumption of 3 characteristic wave-current situations causing various intensity and lithodynamic quality phenomena;
- mean wave height at the 2nd underwater bar (mean depths 2–3 m) as the representative wave parameter for the surf zone;
- because of the method of measurement and evaluation of sediment transport, the prediction of bedload as the main mode of sediment movement.

3. Computations and Results of Temporal Variability of Transport

3.1. Computational Procedure

Temporal (annual) variability of longshore sediment transport can be most easily determined assuming the sequence of relationships given in the Introduction. According to the scheme, the determination of average (daily) wind parameters ($\overline{v_w}, \overline{\varphi}$) is the first step of the procedure. Assuming sequential daily wind situations resulting from nature, one obtains 365 data sets for the period of one year. The annual distribution of averaged (within 1 day) values of wind field ($\overline{v_w}$) and direction ($\overline{\varphi}$) assumed for calculations is given in Fig. 4.

The next step is to determine, for a given time scale, the bathymetry $\bar{h}(x, y)$ represented by a cross-shore profile $\bar{h}(x)$ characteristic at the site.

Taking advantage of Krylov and Battjes & Jansen's models, the mean quantities of wave height ($\overline{H}$) and period ($\overline{T}$), as well as their distributions along a cross-shore profile are predicted. As the characteristic parameter, on the basis of the distribution, the mean wave height ($\overline{H}$) is assumed in the region of the 2nd bar at a depth of $h \approx 2$–3 m. The basic wave breaker occurs most often in

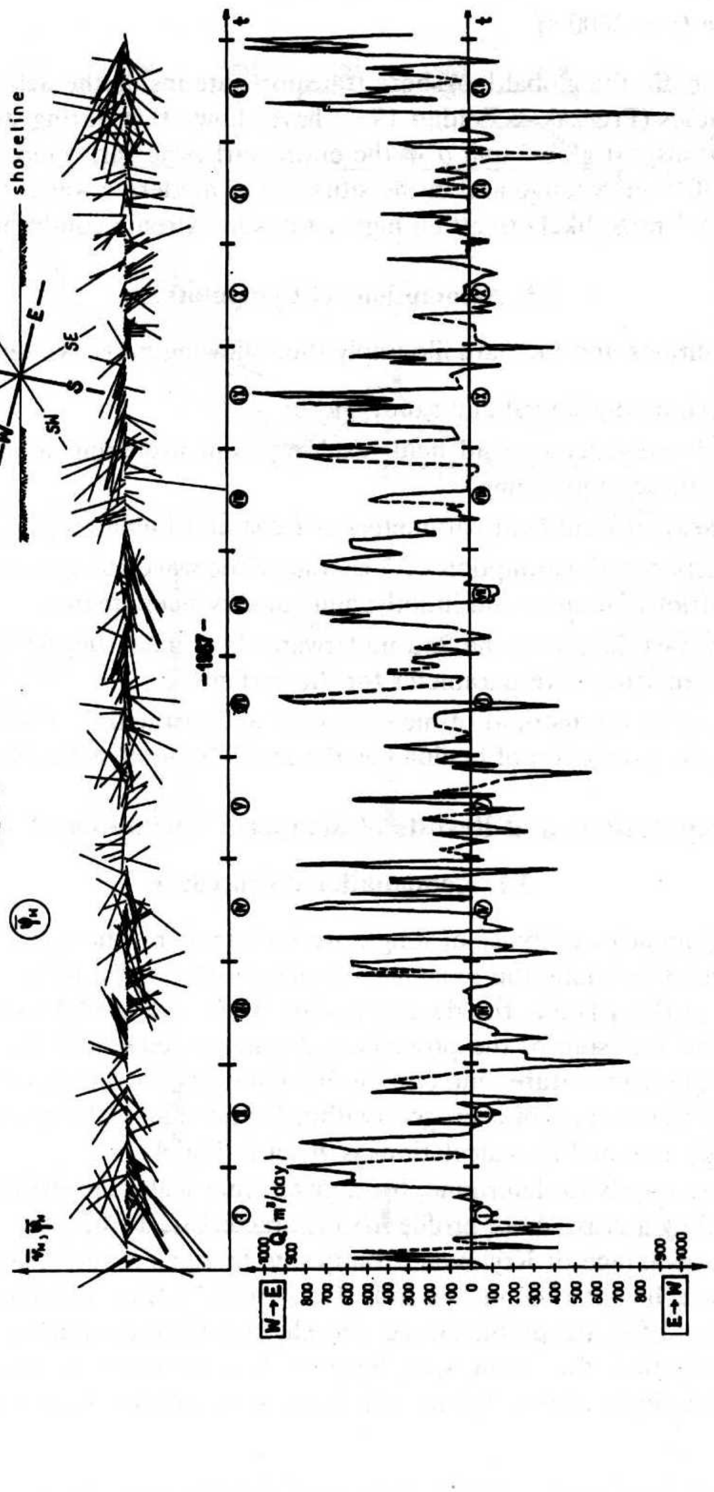

Fig. 4. The annual distribution of averaged (1 day) quantities of wind and longshore sediment transport

this region which is the location of the biggest wave energy dissipation and the most intensive sediment movement, Fig. 3. This makes the 2nd offshore bar the most dynamic point of a cross-shore profile and the local wave parameters are the most representative ones for determination of actual hydrodynamic conditions in a surf zone. As numerous analyses and comparisons proved, the mean wave height predicted with the assumed model represents measured values well. Figure 5 shows the example of such a comparison. The assumed mean wave height ($\overline{H}$) is interpreted as a statistical mean value resulting both from wave spectrum and averaging in time (e.g. daily).

In the next step of the procedure, the longshore current, being a derivative of energy dissipated in the wave breaker ($\partial E/\partial y$), is computed from the Longuet-Higgins model, modified for the case of multi-bar shore by Szmytkiewicz & Skaja (1991). Prediction of the current field, according to assumed computational procedure, has been carried out to determine the mean value of the current $\overline{V}$ for each of two hydrodynamic situations (A) and (B), by the formulae:

$$\overline{V} = \frac{1}{n} \sum_{n} \frac{1}{L} \int_{L} V(x)\, dx \tag{2}$$

where:

n – number of current distributions along a profile, taken into account while averaging,

L – width of surf zone.

The exemplary results of computations of current distributions V and the mean value $\overline{V}$ for situation (A) are given in Fig. 6.

The measurements of longshore currents taken during various experiments at MLB Lubiatowo imply that the mean quantities (averaged over the entire region of actual surf zone) in the case of a strong or stormy wave are of the order of $\overline{V} \approx$ 0.3–0.5 m/s, while for weak and moderate waves one has $\overline{V} \approx 0.1$–0.2 (0.25) m/s (Pruszak & Zeidler 1992).

The instantaneous and local quantities of longshore current can be significantly bigger reaching 1 m/s and more, Fig. 6. The comparison of measurements and computations of longshore currents for situation (A) shows significant agreement (apart from one case). The observations and computations are found to agree with the postulate of Per Bruun (1990), i.e. typical statistical velocity distribution of lonshore current in storm surf zone is almost symmetric with the mean quantity $\overline{V} \approx 0.35$ m/s, the maximum attaining 1.5 m/s. A similar analysis has been carried out for situation (B). According to the above estimation it has been found that situation (A) represents a mean longshore current $\overline{V} \approx 0.35$ m/s while situation (B) gives $\overline{V} \approx 0.20$ m/s.

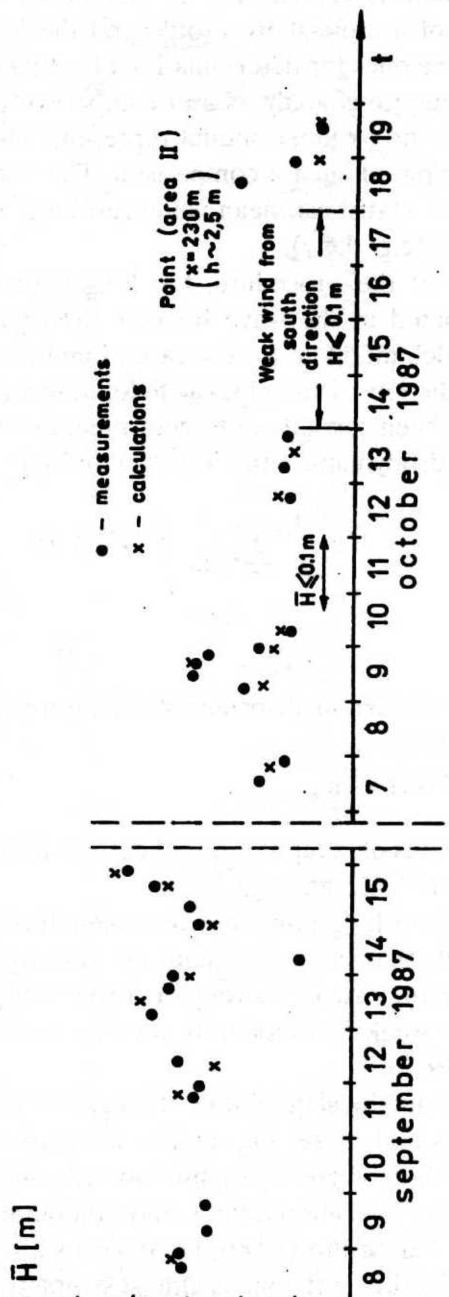

Fig. 5. Comparison between measured and calculated mean wave height for periods 8–15.09.87 and 7–19.10.87

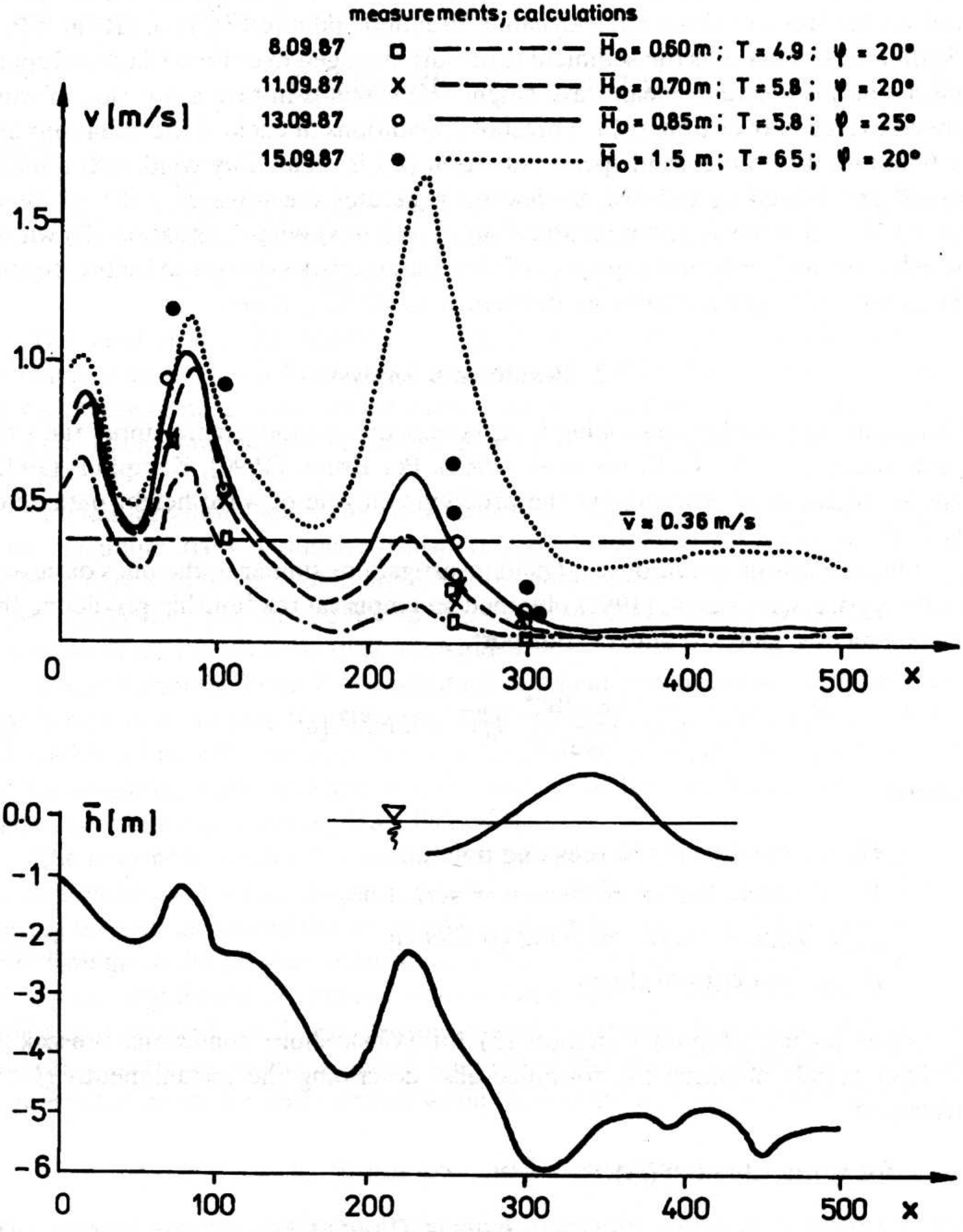

Fig. 6. The exemplary results of computations and measurements of longshore current distributions for the situation (A) in a surf zone

The last step of the procedure is a prediction of sediment movement in the coastal zone. The computations of longshore movement of sediment are carried out on the basis of three hydrodynamic situations denoted by (A), (B) and (C). Within these situations the sediment transport averaged over time (day) and space (surf zone) is linked to mean wave height ($\overline{H}$) which is in turn a function of wind speed averaged over time ($\overline{v_w}$). Threshold conditions in each of the situations are a function of onshore wind speed. Situation (C) is created by wind with a mean speed not exceeding 2–3 m/s. Such wind generates the wave $\overline{H} < 0.1$ m. Wind speed $\overline{v_w} > 3$–4 m/s (but not greater than $\overline{v_w} \approx 8$ m/s) defines situation (B) within which wave and sediment transport of the characteristics discussed before occurs. Situation (A) is generated by an onshore wind of $\overline{v_w} \geq 8$ m/s.

3.2. Results and Analysis

Numerous approaches describing longshore sediment movement imply the proportionality $q \sim H^2 \cdot \overline{V}$, Kraus et al. (1982), Per Bruun (1990), Kamphuis (1991) etc. simultaneously pointing out the predominant role of wave height parameter ($q \sim H^2$).

On the basis of conditions and field investigations similar to the ones discussed in this paper, Kraus et al. (1982) obtained an empirical relationship predicting the instantaneous, global sediment transport:

$$q \approx \frac{3.8 \cdot 10^{-4}}{\gamma_b \tan\beta} H_b^2 \overline{V} = K H_b^2 \overline{V}\ [\mathrm{m^3/s}] \tag{3}$$

where:

H_b – wave height at breaking point,
$\overline{V}$ – mean longshore current in surf zone,
$\gamma_b = H_b/h_b$ – wave breaking coefficient,
β – sea bottom slope.

After having adapted Equation (3) for Polish shore conditions Pruszak & Zeidler (1992) obtained the formulae also describing the instantaneous global transport:

- for storm situation (A)

$$q = 0.015 H_b^2 \overline{V}\ [\mathrm{m^3/s}] \tag{4}$$

- for non-storm situation (B)

$$q = 0.026 H_b^2 \overline{V}\ [\mathrm{m^3/s}] \tag{5}$$

Assuming $H_b \sim H_s = 1.6\overline{H}$ and transforming Eqs. (4) and (5) to a day time scale and taking for situations (A) and (B) $\overline{V} \approx 0.35$ m/s and $\overline{V} \approx 0.20$ m/s, respectively, one obtains the equation valid for both cases:

$$Q \approx 11.6 \cdot 10^2 \cdot \overline{H}^2 \quad [\mathrm{m}^3/\mathrm{day}] \tag{6}$$

where:

$\overline{H}$ – mean daily wave height determined at depth $\overline{h} \approx 2$–3 m (region of 2nd stable bar in the case of multi-bar shore),

$\overline{V}$ – mean daily longshore current averaged over surf zone.

The relationship (6) depicted in Fig. 7 predicts the global daily longshore sediment transport as a function of the mean wave. The figure shows the ranges of variability of parameters which define two basic hydrodynamics situations (A) and (B) being qualitatively representative for two regions of the curve given by Eq. (6).

Annual longshore sediment movement with daily time step is given in Fig. 4. The maximum daily sediment transport rates in analysed conditions attained 1050 m^3/day with the predominant direction from west to east due to the resultant wave energy flux. The dashed line in Fig. 4 denotes transport rates associated with the occurrence of definitely offshore wind.

Within a month, Table 1, the resultant sediment movement was directed eastwards and its maximum rate attained 10000 m^3/month, Fig. 8, while the mean was $Q \approx 4000$ m^3/month. However, there were a few months (spring and autumn) in which longshore transport rates were the same in both directions and the resultant rate was about zero (March, May, October).

The longshore transport sum curve for one year, Fig. 9, indicates the existence of an annual resultant transport of the order of 50000 m^3 directed eastwards. Comparing the sum curve and the assumed line of "uniform increase" of transport one can distinguish the periods of more intensive sediment movement over the period of a year (significant dominance of one (west in this case) direction of transport) and those of small resultant movement (approximate balance of transport in both directions). In the analysed time (year) the first case mentioned above is represented by winter and summer while the second one—spring and autumn.

4. Summary and Discussion

The present analysis evaluates the annual longshore sediment transport in the multi-bar zone. The annual global transport and its monthly (daily) distribution in the function of hydrodynamical (wind) parameters is determined. The global longshore sediment transport per day or longer period of time can easily be found on the basis of either eq. (6) or the curve in Fig. 7 proposed in this paper. One

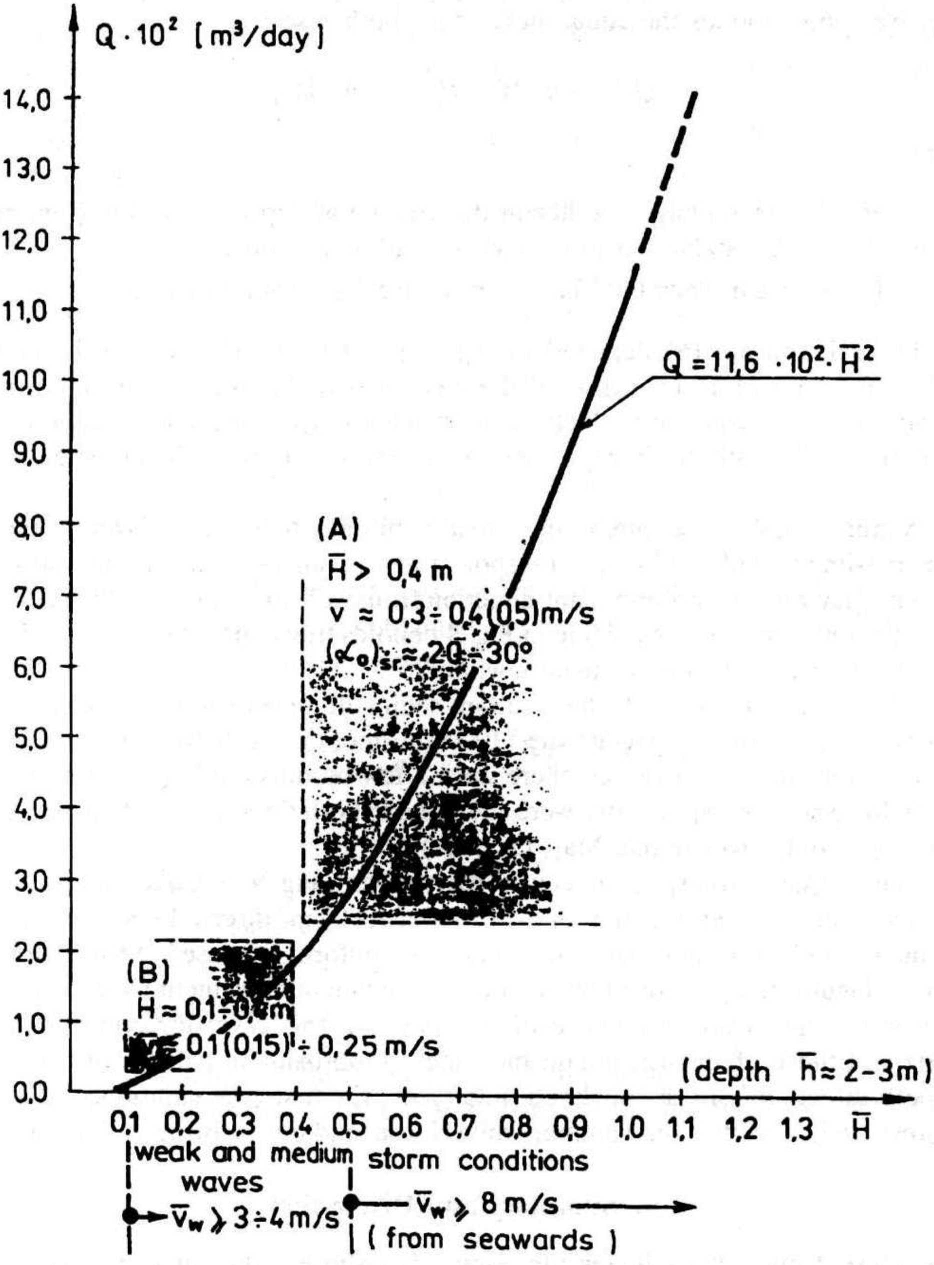

Fig. 7. Global daily longshore sediment transport rate, $Q_s = f(\overline{H})$ (regional hydro- and morphological conditions)

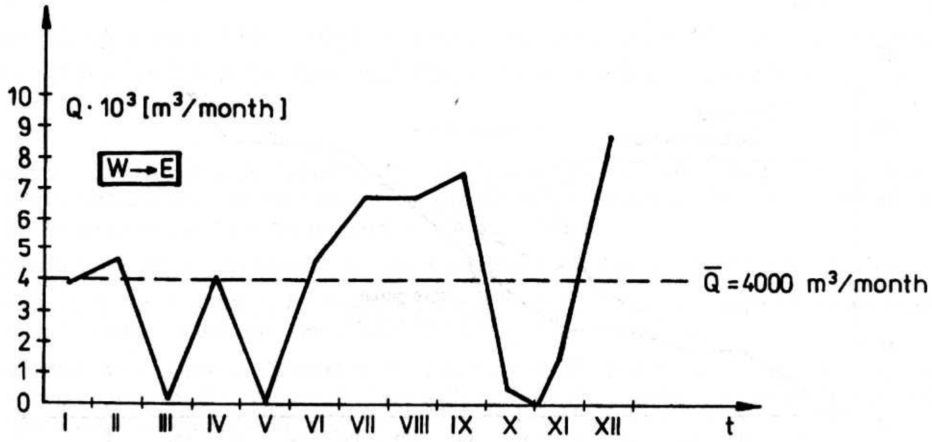

Fig. 8. Monthly resultant longshore sediment transport

Table 1. Estimated values of monthly longshore sediment transport

Month	Direction W → E	Direction E → W	W → E $q_{resultant}$	Cumulative sum
January	5775	1859	3916	3916
February	5216	821	4395	8311
March	2270	2194	76	8388
April	5152	1514	3638	12026
May	1844	1818	26	12052
June	5152	560	4562	16614
July	7354	634	6720	23334
August	6616	48	6568	29902
September	7965	536	7429	37331
October	1055	591	464	37795
November	1952	653	1299	39094
December	9920	1208	8712	47806

Average over a month ≈ 4000 m^3 (mainly bed load)

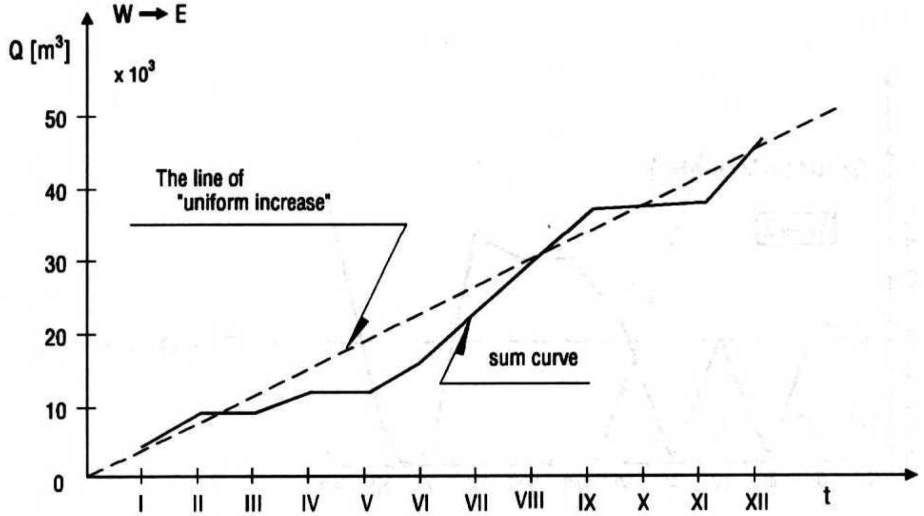

Fig. 9. The longshore sediment transport sum curve

only needs to know the mean daily wave height ($\overline{H}$) about 2nd bar, (Fig. 3), as this plays the key role in the case of a multi-bar shore. The mean wave height input ($\overline{H}$) can be estimated either by computations from daily wind parameters and cross-shore profile shape or directly by measurements.

The accuracy of estimation or prediction of daily longshore sediment transport by the proposed method depends on the degree of stationarity of the wind field. The most perfect conditions are a homogeneous wind field within the analysed time period (a day) and the resulting wave-current field.

Given rates and distributions of longshore sediment transport correspond to definite hydrological-morphodynamic conditions of the coastal zone. The latter encompass the dominance of oblique approach of waves to the shore, multiple breaking of wave, a multi-bar, mildly sloped ($\beta \approx 1.5\%$) shore, grain characteristics ($D_{50} \approx 0.022$ cm, $\varrho_s \approx 2.65$ g/cm^3) etc. Assuming these features as general parameters, often common for various shores, obtained rates of sediment transport can be regarded as indicators valid for other similar shores.

The intensity of sediment movement resulting from the proposed procedure and equation (6) can in some cases be slightly underestimated as regards the total real sediment transport rate. This results from the use of empirical relationships derived on the basis of tracer measurements of sediment movement. The bedload is mainly taken into account in such methods while the suspended load can be underestimated. This refers first of all to cases of severe storms when a great amount of sediment moves in suspension.

The analysis of annual variability of longshore sediment transport does not confirm the frequent opinion as regards much greater intensity of winter transport as compared with summer. The meteorological situation which may not be typical for the year analysed plays a basic role in this case.

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