CHAPTER 182

Sediment Transport in Various Time Scales

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Abstract

Some basic sediment movement characteristics such as critical velocities of motion, bed load layer thickness, as well as local and overall sediment transport have been measured in field at Lubiatowo, Poland.

The survey was carried out in a multi-bar (4–5 bars) Polish coastal zone with the medium grain diameter D_{50} from 0.2 to 0.25 mm. Irydium glass grains tracer, close in size to the natural sand, has been used. The investigations embodied 8 hydrodynamical situations in various climates of waves and currents.

For oblique wave incidence it has been found that local intensity of longshore sediment transport can reach 40–100 kg/(m h) under storm conditions, strongly dependent on local bed topography. The overall sediment transport rate across the entire surf zone can exceed $7 \cdot 10^{-3}$ m^3/s under storm conditions. For weak wave motion the bed surface layer of sediment transport has a thickness of several grain diameters, while it may be even 4–6 cm thick during storms. Vertical distributions of sediment concentration beneath of bed surface are identified. Transport rates are related to the product of squared breaker height and longshore velocity. Annual time series of sediment transport are presented.

1 INTRODUCTION

Coastal zone is characterized by intensive sediment transport and considerable morphodynamic changes. Because of its importance as an interface of the atmosphere, the sea, the land and engineering structures, its dynamics should be well understood.

Some primary quantities describing sediment transport in the coastal zone include critical speeds of incipient movement, thickness of the bedload layer and velocity distribution within this layer, and the resulting bedload transport rate.

For the purposes of this study, we distinguish short-term changes (hours, at most days) mainly associated with a single storm, meso-scale ones (weeks or months) and long-term changes (years or decades). In this paper, emphasis is placed on the first and third scale.

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Field studies provide a reliable background for understanding coastal processes and drawing conclusions on various estimates of sediment transport quantities. Numerical models are still inaccurate and require validation based on field measurements.

This paper describes results of recent field studies, thus expanding the earlier investigations by Pruszak & Zeidler (1992). The sediment transport experiments were carried out at the IBW PAN Coastal Research Facility off Lubiatowo.

2 FIELD DATABASE

The Coastal Research Facility (CRF) at Lubiatowo is situated on the southern Baltic beach and shore of transitional nature, which experiences neither accretion nor erosion in long time scales. The short-term variability of shore processes is evidenced by cyclic occurrence of erosion bays or accretion cusps every 30 years (Pruszak 1993).

The shore at Lubiatowo is dissipative mild slope one with conspicuous four bars about 110, 190, 370 and 650 m from shoreline (Fig. 1). An ephemeral unstable bar is sometimes visible close to the shoreline (some 30–40 m away). The median grain diameter D_{50} varies between 0.2 and 0.25 mm. The littoral drift is substantial since the net annual wave momentum flux is oriented obliquely to the shoreline. Wave breaking in the Lubiatowo surf zone is pronounced at a few locations, identified with underwater bars. During average storms the significant wave reaches the height $H_s \approx 2$–3.5 m with the period T from 5 to 7 s at the seaward boundary on the depth of 7 m. As a result of the subsequent transformation, the mean wave height falls to 1–1.5 m on the depth of 2–3 m (about the second and third bars) while the mean wave period becomes 4–5 s.

Along with parameters of wind, waves, currents and other hydrologic factors, topographic features have been measured at Lubiatowo since 1983 on a 2.7-km beach and nearshore zone extending some 800 m from shoreline. The beach profiles have been arranged every 100 m, and have been recorded every four weeks. Subaqueous profiles extending to about 100 m from shoreline have been measured systematically every four weeks since 1991.

In our tracer studies of sediment transport we have been using irydium glass grains close in size to the natural sand. The half-life period of the radioisotope is 74.4 days.

The 1993–1994 field campaign included *inter alia* the disposal of six tracer batches at six different locations of the Lubiatowo coastal zone, as depicted in Figure 1. The disposal points were chosen so as to monitor the three characteristic subareas of the coastal zone shown in Figure 1, as already pursued by Pruszak & Zeidler (1992).

The sediment transport investigations were carried out in two series in autumn 1993 and spring 1994. Simultaneous measurements of waves, currents and wind were conducted during the radioisotopic studies. The measurements were continued regularly every three hours at two locations of the surf zone denoted by D1 and D2 in Figure 1. An exemplary record of wind, waves and currents along and across shore is given in Figure 2.

Ninety four core samples 40 cm in length were taken from the sea bed. The samples originate from various areas coupled with the movement of tracer plumes. The samples were analysed in 2-cm layers by the use of a very sensitive scanner. Both location and intensity of the radiotracer in plumes was measured from a boat with a special monitoring and recording apparatus. Examples of

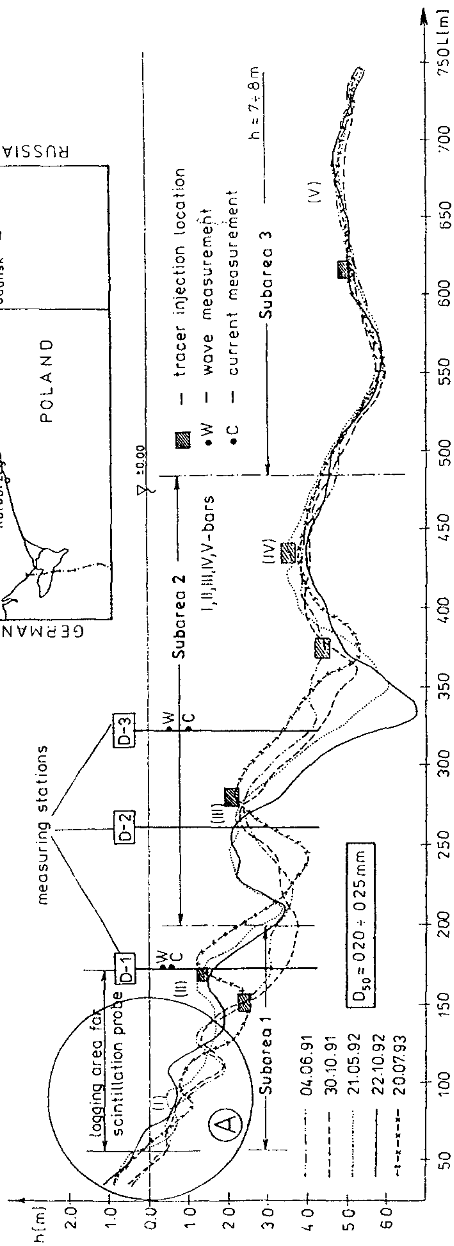

Figure 1. CRF Lubiatowo, bottom topography and measuring arrangements.

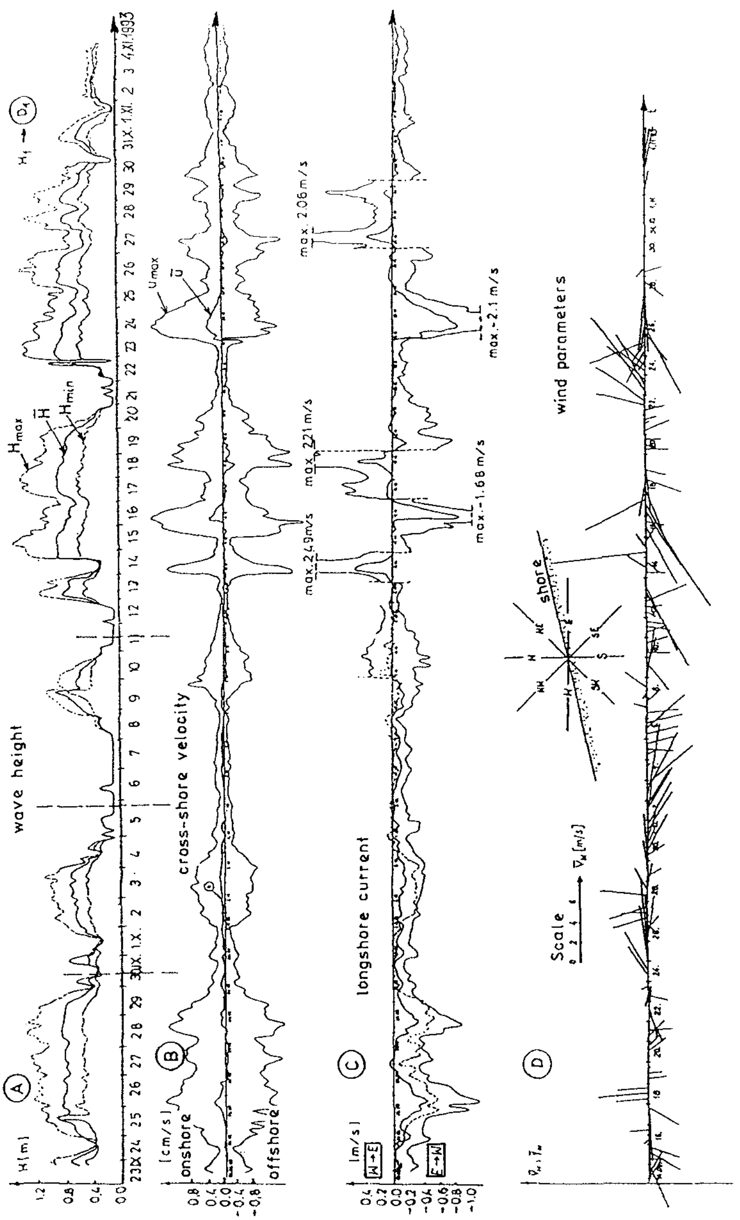

Figure 2. Wind, wave height, cross-shore and longshore velocity at CRF Lubiatowo during the 1993 field studies.

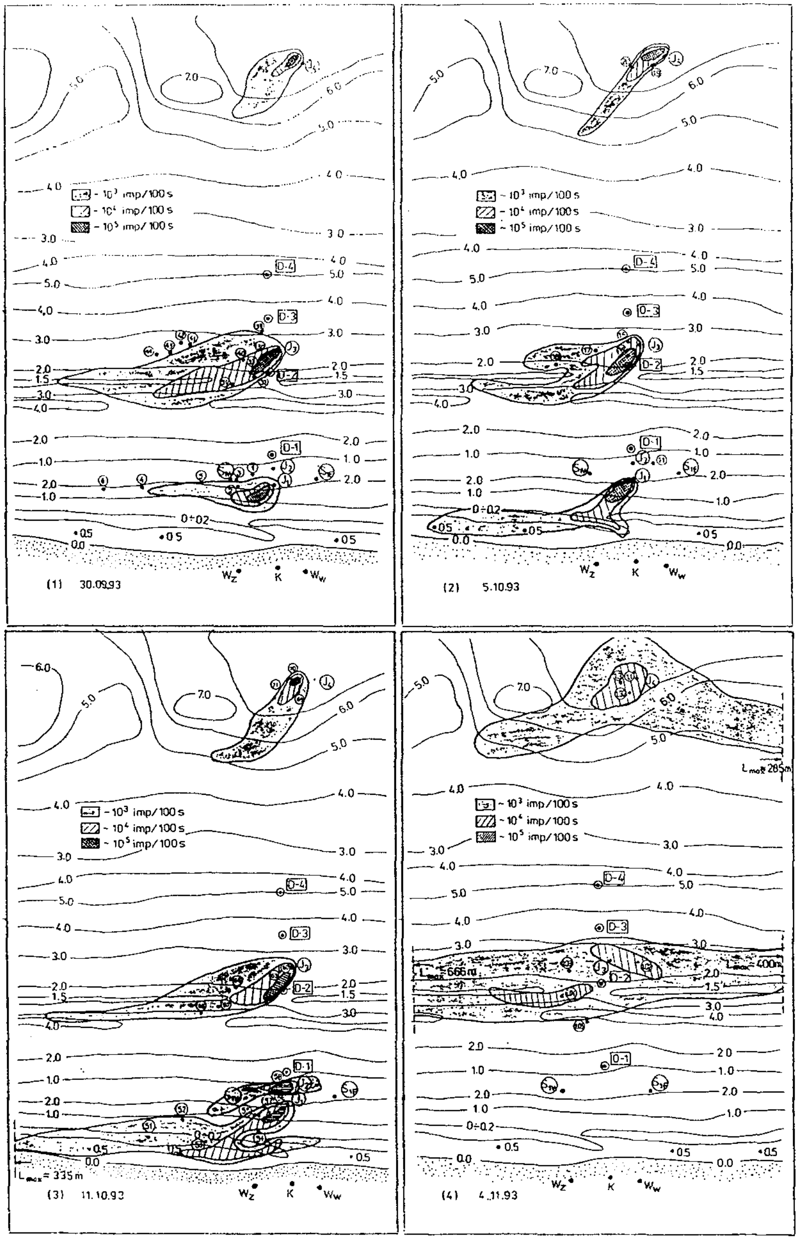

Figure 3. Radiotracer plumes at CRF Lubiatowo, fall 1993; (52) etc. tracer sampling location, (imp) - pulse; (I) - injection spot; (S) - sand trap

subsequent locations of 3-4 plumes out of total six are shown in Figurc 3 for the first measurement scries of autumn 1993.

Simultaneously with the observations and measurements of the radio-tracer, measured at two locations of the surf zone were suspended loads up to 2 m above sea bed, at stations denoted by S_{1E}, S_{1W} and S_4, as in Figure 3. The suspended load was mcasured separately for longshore and cross-shore directions. Tracer grains were identified in every sample.

3 SEDIMENT MOVEMENT FIELD STUDY

3.1 *Critical velocities*

Two primary thresholds of sediment transport can be identified under waves and currents:

- incipient motion of single grains $V_{cr}^{(1)}$
- critical velocity of bulk transport identified with the movement of the bed-load layer having the thickness a, i.e. $V_{cr}^{(2)}$.

From recent investigations, including those by Pruszak & Zeidler (1988), it is known that the motion of single grains having the median diameter D_{50}=0.10-0.25 mm and the density ρ_s=2650 kg/m^3 occurs at $V_{cr}^{(1)} \approx$ 8-12 cm/s. In exceptional cases coupled with local bathymetry and random disturbances of wave motion, those velocities can be smaller than 8 cm/s or greater than 12 cm/s, up to 20 cm/s.

The other sediment transport threshold lies at $V_{cr}^{(2)} \approx$ 40-50 cm/s or even 20 cm/s for fine particles having D_{50}=0.08-0.10 mm. The bulk motion of sediment grains can obviously occur in layers of different thickness. It can be assumed that the incipient motion occurs in a thin layer of a few sand grains when the flow velocity reaches about 30-40 cm/s, and it is fully developed at currents reaching 50-70 cm/s, when the moving layer of sediment is considerably thicker.

3.2 *Sand grain speed*

Once the critical velocity $V_{cr}^{(1)}$ is surpassed, the sediment is likely to move in a very thin surficial layer. The grain speed at the mud line v_{ml} will depend on the intensity of water flow. As the latter increases, the grain speed will also change but the sediment at the mud line will move much faster than that beneath. The bulk motion of sediment in the deeper layers is much slower than the mud line velocity v_{ml} as illustrated in Figure 4. Sediment grains participating in the mud line motion are much more mobile and their speeds exceed that of the deeper layers by a factor of two and more.

The discrimination of the bed surface layer at mud line and bulk transport of sediment grains is schematized on the right hand side of Figure 4. The experimental relationships between the mean grain speed and water velocity for the two distinct sediment layers are shown on the left hand of the same drawing. In our analysis of sediment transport characteristics in the above layers, we have followed the distinction of three characteristic subareas of the coastal zone having different hydrodynamic and morphodynamic conditions, as identified at CRF Lubiatowo by Pruszak & Zeidler (1992), cf. Figure 1.

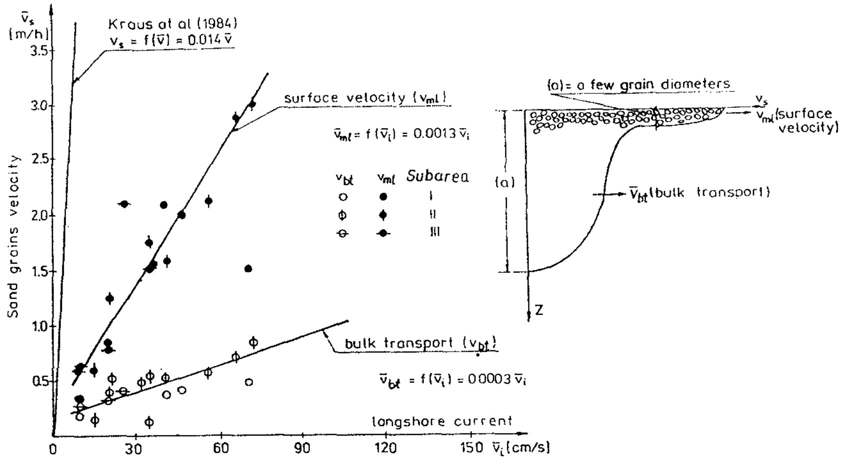

Figure 4. Mean longshore sediment speed versus velocity of longshore current

The mean longshore mud line velocity of sediment grains within the entire active cross-shore profile is given as follows:

$$\overline{v_{ml}} = 0.0013\overline{V_i} \tag{3.1}$$

while the bulk transport velocity reads

$$\overline{v_{bt}} = 0.0003\overline{V_i} \tag{3.2}$$

where $\overline{V_i}$ = longshore current velocity averaged over respective subarea (i = 1, 2 or 3).

The sediment transport velocities obtained for the Polish conditions of the South Baltic are smaller by an order of magnitude than those given by Kraus et al. (1982). The discrepancy indicates that such relationships are regional and depend on local parameters. It should be noted that the grain speed given by Kraus et al. (1982) is presented as a function of the longshore current velocity averaged across the entire shore profile, not a specific subarea, as in our analysis.

3.3 *Bedload layer thickness*

Examples of a few vertical distributions of the radiotracer in the three subareas of motion are presented in Figure 5. Zero denotes that the radioactivity of the selected layer was smaller than 600 pulses/100 s, that is below the natural background of sea bed activity. Upon thorough analysis of the obtained distributions one can identify stratification of sediment transport in sea bed. Major concentrations of the radiotracer occur at the mud line and seldom deeper than about

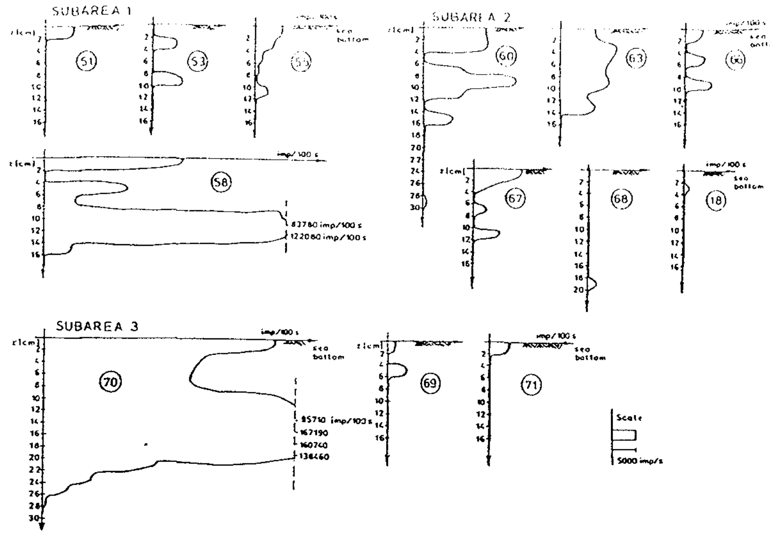

Figure 5. Vertical distributions of bedload as jugded from the 1993 tracer studies at CRF Lubiatowo; (imp) pulses.

15 cm below mud line. It was only in one case that tracer concentration of 640 pulses/100 s was detected 30 cm below bed surface (sample No. 70). In that case the sample was taken in the immediate vicinity of the disposal point, and the initial radioactivity was rather high. The results and the analysis suggest that it is only during storms that the bed surface layer of moving sediment exceeds 2 cm in thickness, while the latter can be assessed at a few or several grain diameters for average waves, whereas the maximum thickness of 4-6 cm could be expected at very severe storms. The thickness of the bedload layer also depends on local bed topography. Considerable differentiation of the thickness is noted about an underwater bar crest.

It should be emphasized that the values given above refer to the active bedload layer in which all moving sediment grains are in motion at the same time and move in the same direction.

From our recent and earlier investigations it can be concluded that the bedload layer thickness corresponds to the estimate given by Kraus et al. (1982):

$$a = 0.027 H_b \tag{3.3}$$

in which H_b = breaker height at a depth of 2-3 m (about the second bar).

3.4 *Sediment transport*

3.4.1 *Cross-shore transport*

Sediment transport rate can be computed by the following formula:

$$q = q_{ml} + q_{bt} = (\rho_s - \rho)(\bar{v}_{ml} a_{ml} + \bar{v}_{bt} a_{bt}) \tag{3.4}$$

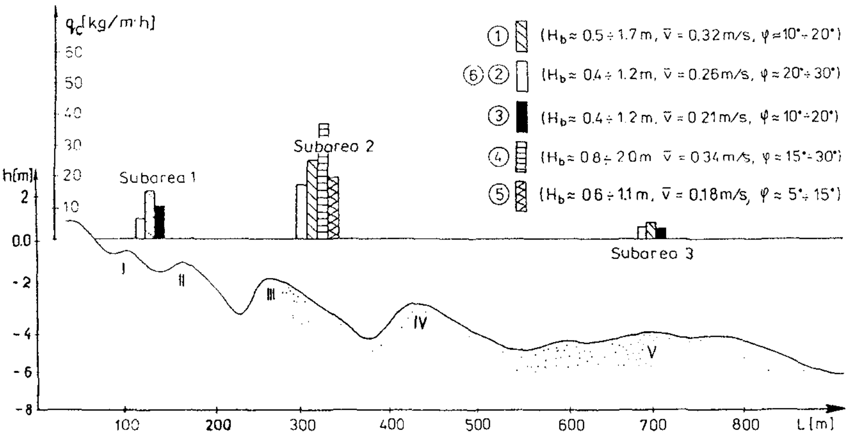

Figure 6. Cross-shore distribution of cross-shore sediment transport rate in five classes of waves.

where $\bar{v}$ denotes time-averaged sand speed (either along or across shore), the index ml denotes mud line and bt stands for bulk motion.

The most intensive net cross-shore transport occurs at the second and third bar in the cases of average or high waves, as illustrated in Figure 6. The sediment transport rate at crests of those bars can reach 25 kg/(m h) during storm phases. Local maxima can even amount to 35-40 kg/(m h). The transport rate decreases in the seaward direction and for the average wave conditions it is about 5-10 kg/(m h) in subarea 3. For the predominant oblique wave incidence it can be assumed that a local ratio of cross-shore transport rate to the longshore one oscillates about 1:3–1:4. However, it should be noted that the above mean values can deviate substantially from instantaneous rates because of the high variability of sediment transport.

It has been found that the cross-shore transport in the troughs between bars is negligible, so that practically all grains move about bar crests. The resulting movement of sediment in the cross-shore direction can be coupled with the displacement of bar crests. The latter can be both landward and seaward.

3.4.2 *Longshore sand transport (local)*

The longshore sediment transport depends on the nature and intensity of waves and currents and on local topography. In local terms, the sediment transport is a function of sand grain speed v and the thickness of transport layer a, and can be approximated as follows:

The cross-shore variability of the longshore sediment transport rate computed by Equation 3.4 is illustrated in Figure 7 for a few selected wave-current cases. The most intensive longshore sediment transport appears to occur at sec-

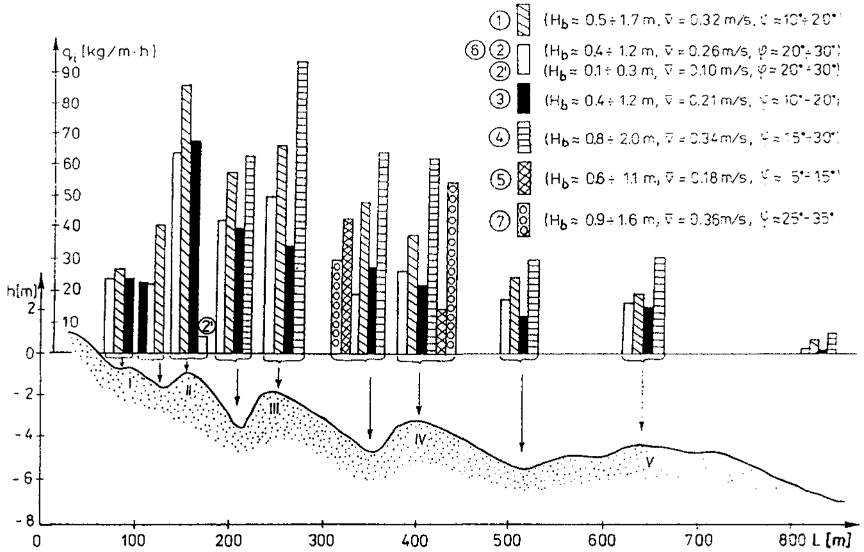

Figure 7. Cross-shore distribution of longshore sediment transport rate in five classes of waves.

ond and third bars, and decreases both seawards and shorewards. It is worthwhile to note the existence of a relatively high sediment transport in between bars, particularly in areas of the prevailing wave breaking, in our case again about second and third bars. This finding is not widespread, and contrary arguments on the low importance of the troughs in the overall longshore sediment transport have often been raised. In many instances, particularly at smaller wave incidence angles, the longshore sediment transport rate between bars is of the same order as that on bars. In some situations the troughs did not permit cross-shore spreading of sediment, especially if they were deeper and steeper.

By and large, the longshore sediment transport under weak waves (breaking between second bar and shoreline, with breaker height much lower than 1 m) occurs only in subarea 1, and its rate does not exceed 5-8 kg/(m h). As the wave height increases (wave breaking between third bar and shoreline, mean breaker height slightly below 1 m), the longshore sediment transport occurs in a wider surf zone and extends up to the fifth bar at maximum. Depending on local longshore current and wave parameters, the longshore sediment transport rate may vary between 5-30 kg/(m h) in subareas 1 and 2 and 0-15 kg/(m h) in subarea 3.

The longshore sediment transport rate increases substantially under storm conditions, when waves break far away from shoreline and at many locations across the surf zone, with the mean breaker height above 1 m. Hence in subarea 1 the local magnitude of q_l reaches 100 kg/(m h) and varies from 40 to 100 kg/(m h) about bars. In subarea 2 the longshore transport is similar, but often even exceeds the earlier magnitude. In subarea 3 the transport rate decreases considerably, and falls to 30 kg/(m h) about the fifth bar. Further seawards one observes transport rates falling to 5–10 kg/(m h) at depths of 6–7 m. Obviously, the transport rate can be higher under extreme storms. In general, the longshore transport rate during storms is a few times greater than at average waves.

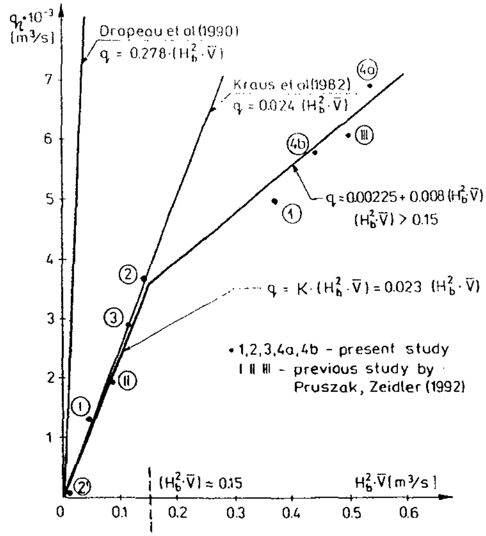

Figure 8. Dependence of littoral drift rate on the product $H_b^2\bar{V}$.

3.4.3 *Littoral drift rate*

From our experiments and the analysis of the obtained data it follows that the littoral drift rate i.e. the overall longshore transport rate across the coastal zone (assumed 950 m wide for the purposes of this study) reaches $3\text{-}7\cdot 10^{-3}$ m³/s under conditions of intensive waves approaching the shore at angles from 10 to 30°. Of course, local unit transport rates vary across the shore, as pointed out above. If waves are very high and conspicuously oblique then the transport rate can exceed $7\cdot 10^{-3}$ m³/s, while at lower waves under our conditions the transport rate varied from $0.35\cdot 10^{-3}$ to $2\text{-}3\cdot 10^{-3}$ m³/s.

The overall longshore transport rate can be presented as a function of $H_b^2 \cdot \overline{V}$, where $\overline{V}$ represents the mean longshore velocity of water. It appears that the relationships between the sediment transport rate and that quantity (Fig. 8) can be approximated by two straight lines. For smaller values of the quantity $H_b^2 \cdot \overline{V}$=0-0.15, thus small and medium waves, the function $q = f(H_b^2 \cdot \overline{V})$ reads:

$$q_l = K(H_b^2 \cdot \overline{V}) = 0.023(H_b^2\bar{V}) \tag{3.5}$$

For higher waves and storms, with $H_b^2 \cdot \overline{V}$ >0.15 the function is as follows:

$$q_l = q_0 + K_1(H_b^2 \cdot \overline{V} - 0.15) = 0.00225 + 0.008(H_b^2\bar{V}) \tag{3.6}$$

It seems that the above relationships can be used for the forecast of the overall longshore transport rate in short time scales.

Upon comparison of the results obtained under this study and our earlier investigations (Pruszak & Zeidler 1992), versus other sources of data, one can say that the formula must be site specific. From investigations by Drapeau et al.

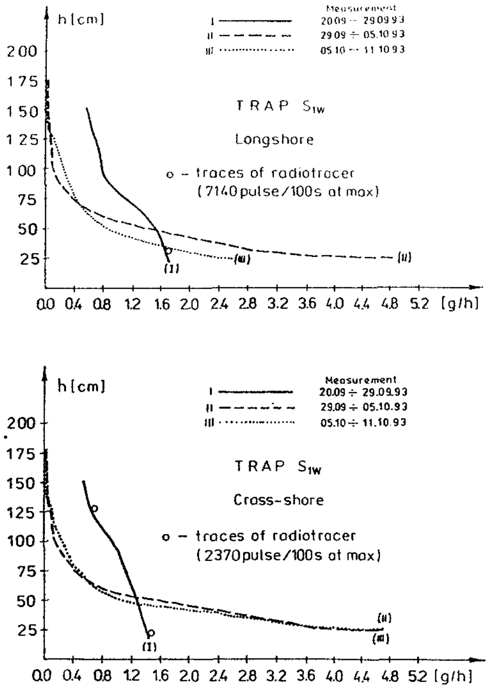

Figure 9. Vertical distributions of sediment concentration in sand traps; trap slots aligned along shore (upper) and across shore (lower).

(1990) carried out in the North Atlantic in the presence of strong tides it follows that the proportionality factor K in Equation 3.5 is 0.278. On the other hand, Kraus et al. (1982), under mesotidal conditions, obtained $K=0.024$. It may be seen that this proportionality factor coincides with ours up to $H_b^2 \cdot \overline{V}=0.15$, while a conspicuous deviation is noted for higher values of that parameter, i.e. higher waves.

3.4.4 *Suspended sediment*

The concentration of suspended sediment is higher in subarea 1, with predominant wave breaking and high turbulence, than in subarea 3. Under storm conditions (cf. Fig. 2), the sediment was picked up from the sea bed in subarea 1 to reach the free surface. In cases of less intensive waves (situations II and III) the sediment was kept in suspension up to 1-1.2 m above bed, that is middepth at the investigated location (Fig. 9).

The radioactive tracer was disposed of some forty metres away from sand traps. It was found at different elevations up to 1.3 m above bottom. This indicates that the radiotracer moves not only as bedload but also in suspension, quite high above sea bed. The proportions between bedload and suspended load are difficult to define as they depend on many factors such as intensity of wave mo-

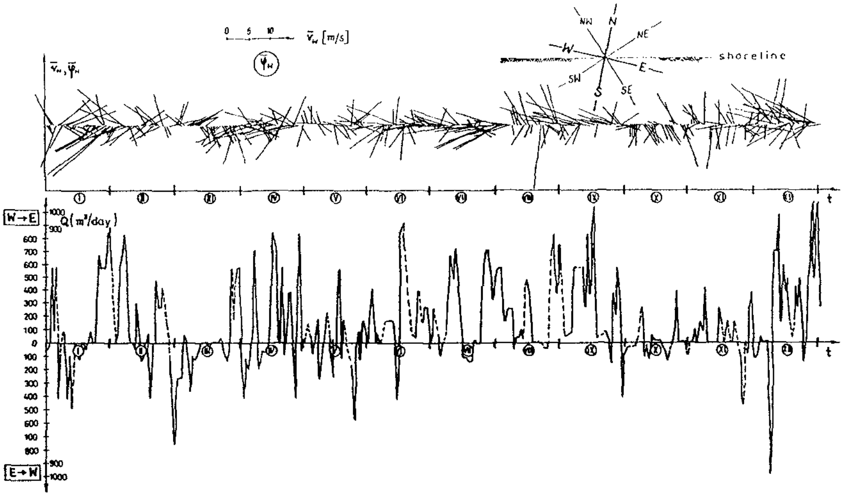

Figure 10. Annual time series of wind (upper) and the resulting littoral drift rate (lower).

tion, circulation and currents, local topography and sediment properties. From different observations and estimates, including those with radiotracers, it can be assessed that about 70-80% of total transport belongs to bedload under weak wave conditions, or even about 100% in exceptional cases. On the other hand, storm conditions bring about intensive suspension, and bedload and suspended load become of the same order, whilst suspended load can clearly predominate under very intensive storm conditions. The latter structure is typical of the surf zone, about wave breaking line and on small depths. On greater depths bedload seems to prevail. It should also be added that suspension is usually preceded by bedload.

3.4.5 *Mesoscale sediment transport*

From many observations and investigations it appears that major effects of the longshore sediment transport are noted in time scales counted in days, months and even years. Our field studies provide a certain insight into the yearly structure of the longshore sediment transport. If one averages over a day the causative sequence of events bringing about the sediment transport (wind, waves, currents, sediment transport), then one obtains a picture permitting conclusions on the yearly structure of sediment transport rates. This is illustrated below and in Figure 10 where both wind input and the resulting sediment transport itself are shown. It should be recollected that only causes, not sediment transport itself are measured in the yearly series. The sediment transport rate was computed from Equations 3.5–3.6.

From our computations and the distributions shown in Figure 10 it appears that although daily transport rates can exceed 1000 m^3/day (across the entire surf zone), the resulting mean net monthly rate is only 4000 m^3/month, corresponding to the mean annual rate of 50000 m^3. It is also visible that the yearly course of sediment transport is stepwise: some 25% of the mean monthly amount of sediment transported can be derived from a single storm.

4 CLOSING REMARKS

Upon comparison of our results with other investigations and findings it can be concluded that many sediment transport formula are site specific, or depend on particular environmental properties embedded in those formulae. Hence from studies by Drapeau et al. (1990) for the North Atlantic and strong tidal effects it appears that the parameter K is 0.278. Kraus et al. (1982) conclude that K is 0.024 for a nontidal shore with a single bar. On the other hand, from our measurements for the Polish Baltic conditions the coefficient is identical with Kraus's if the characteristic quantity $H_b^2\overline{V}$ <0.15 predominates, while it deviates considerably if that quantity is above 0.15, i.e. for intensive wave conditions. The observations, measurements and conclusions drawn for the two ranges of $H_b^2\overline{V}$ above and below 0.15 add an interesting message to the linkage between sediment transport rate and its causes.

No matter how approximate and incomplete, the annual distribution of sediment transport rate shown in Figure 10 for the Polish Baltic conditions contains an important information on the stepwise nature of sediment transport. The estimates shown can be regarded as typical of the southern Baltic.

It is worthwhile to emphasize our finding that the sediment transport between bars can be quite conspicuous particularly at locations of the most frequent wave breaking (our bars II and III) This is contrary to the widespread belief that the sediment transport in troughs is much less important than that on bar crests.

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