CHAPTER 188

# ACCURACY AND APPLICABILITY OF THE SPM LONGSHORE TRANSPORT FORMULA

by
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## ABSTRACT
The ability to predict the time-averged longshore sediment transport rate accurately is essential for many coastal engineering applications. Because the longshore transport formula in the Shore Protection Manual (SPM; US Army, Corps of Engineers, 1984) is possibly the most widely used, it is important to know its accuracy. The aim of this paper is therefore to investigate the accuracy and applicability of this formula (the SPM formula). In addition, a number of variations to this formula are presented; these are also tested against a comprehensive data set. Finally, the SPM formula is re-calibrated and guidance is given regarding the use of this formula for coarse bed material.

## INTRODUCTION
The ability to predict the time-averaged longshore sediment transport rate accurately is essential for the design of breakwaters at harbour entrances, navigation channels and dredging requirements, beach improvement schemes incorporating groynes, detached breakwaters and beach fill as well as for the determination of the stability of inlets and estuaries.

Because the longshore transport formula in the Shore Protection Manual (SPM; US Army, Corps of Engineers, 1984) is possibly the most widely used, it is important to know its accuracy. The aim of this paper is therefore to investigate the accuracy and applicability of this formula (the SPM formula). In addition, a number of variations to this formula have been presented; these will also be tested against a comprehensive data set. Finally, the SPM formula is re-calibrated and guidance is given regarding the use of this formula for coarse bed material.

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The data considered in this paper are only for particulate (non-cohesive) sediment (including sand, gravel and shingle) being transported alongshore from the swash zone across the surf zone to deep water. Only bulk (total rate across the shore) and not local transport rates are considered. These bulk rates include both the bedload and suspended load. Only field data are used because of possible scale effects in laboratory investigations and/or because regular waves were used. Furthermore, the ultimate aim is to be able to predict longshore transport accurately in the field (Komar, 1988).

The data are not meant to provide average long-term data at (a) specific site(s). It is rather assumed that if a longshore transport formula is capable of accurately predicting transport rates for the data sets given herein, it can be used with reasonable confidence at similar sites to determine the long-term longshore sediment budget if representative wave and other input parameters are available. It would of course be even better to have site-specific calibration data before calculating average long-term transport rates.

Previous studies where a few longshore transport formulae have been tested against data are Swart (1976), Fleming *et al.* (1986) and Kamphuis *et al.* (1986). Schoonees (1994) evaluated 51 formulae against an extensive data base. This paper reports the findings of the above-mentioned study with regard to the SPM formula and variations thereof. Two of the most important papers on the development of the SPM formula are Komar and Inman (1970) and Komar (1988). The latter study in which the dependency of the SPM formula on sediment grain size, beach slope and wave steepness was investigated, is partially revised here with a bigger data base.

## DATA

Schoonees and Theron (1993) compiled and reviewed almost all the available field data on longshore transport. They used a point rating system to assess the quality of the data in detail. Two data sets, namely Data Sets 1 and 2, were extracted from the data contained in Schoonees and Theron (1993) together with their point ratings.

Data Set 1 containing 123 data points, consists of data where all the required parameters are available. Table 1 summarizes this data set and gives the point ratings in percentages according to Schoonees and Theron (1993). Data Set 2 includes Data Set 1 and contains other measurements totalling 240 data points. These other measurements are usually where only values of the energy flux factor, the longshore transport rate and the median grain size are available. Table 2 lists the sources of Data Set 2.

It is important to note that the data ranges of the particular Data Set 1 are:

| | | | | |
|---|---|---|---|---|
| 0,058 | $<$ | $H_{bs}$ (m) | $<$ | 3,400 |
| 2,32 | $<$ | $T_p$ (s) | $<$ | 16,60 |
| 0,30 | $<$ | $\theta_b$ (°) | $<$ | 35,00 |
| 0,0070 (=1/142,9) | $<$ | beach slope | $<$ | 0,1380 (=1/7,2) |

| | | | | |
|---|---|---|---|---|
| 0,154 | < | $D_{50}$ (mm) | < | 15,000 |
| 600 | < | S ($m^3$/year) | < | 14 793 000 |

From the above values it is clear that the data ranges of this data set (and therefore also Data Set 2) are quite wide. Most conditions encountered on natural beaches are covered and the data were collected on beaches from a variety of sites from around the world. These give credibility to the conclusions drawn in this comparison with data.

## FORMULAE

One of the earliest longshore transport formulae and perhaps the best-known method, the **SPM formula** (SPM = Shore Protection Manual) is given in US Army, Corps of Engineers (1984):

$$S = K_1 P_{ls} \quad (m^3/yr)$$

where $K_1$ = 1289 ($m^4$/(W.yr) for prototype beaches

$P_{ls}$ = wave energy flux factor using the significant wave height in the calculation. (W/m)

$= E_b \, n_b \, C_b \sin \theta_b \cos \theta_b$

with $E$ = wave energy density

$= \rho g H_{bs}^2 / 8$

$\rho$ = density of sea water (kg/$m^3$)

$g$ = gravitational acceleration (m/$s^2$)

$H_{bs}$ = significant breaker wave height (m)

$n_b$ = $0{,}5\,(1 + (4\pi d_b/L_b)/(\sinh 4\pi d_b/L_b))$

and $d_b$ = breaker depth (m)

$L_b$ = wavelength at the breaker line (m)

$C_b$ = wave celerity at the breaker line (m/s)

$= (L_b / T_p)$

$T_p$ = peak wave period

and $\theta_b$ = wave incidence angle at the breaker line

An alternative formulation of the SPM is:

$$I = K_s P_{ls} = K_r P_{lr}$$

with $I$ = immersed weight longshore transport rate

$P_{lr}$ = energy flux factor using the root-mean square breaker height

where $K_s$ = 0,5 (0,78) = 0,39 if the significant breaker height is used in $P_{ls}$

$K_r$ = 0,78 if the root-mean-square breaker height ($H_{brms}$) is used in $P_{lr}$

Development of the SPM formula was done, among others, by the Scripps Institute of Oceanography (1947), Watts (1953), Caldwell (1956), Inman and Bagnold (1963), Komar (1969), Komar and Inman (1970) and Komar (1988).

**Swart** (1976) adapted the coefficient $K_1$ = 1289 to be a function of the median grain size ($D_{50}$). His version of the **SPM formula** which appears to differ from the SPM formula given above because of several implications, is

$$S = K_2 \, P_{ls} \qquad (m^3/yr)$$

where $K_2$ = $1876 \log_{10} (0{,}00146 / D_{50})$
($D_{50}$ in m)

This equation together with a relationship proposed by Bruno *et al* (1981) will be shown later. Komar (1988) maintained that there is no significant relationship between $K_1$ and $D_{50}$. This issue will be discussed further based on all the data.

**Kamphuis and Readshaw** (1978) and Vitale (1981) investigated whether $K_1$ is a function of the surf similarity parameter (or Iribarren number) $\xi_b$:

$$\xi_b = \frac{\tan\alpha}{(H_{brms}/L_o)^{0,5}}$$

where $\tan \alpha$ = bottom slope in the surf zone

$H_{brms}$ = $H_{bs} / \sqrt{2}$

$L_o$ = deep-sea wavelength

Vitale (1981) used a mean wave height (measured in relatively deep water) instead of $H_{brms}$. To prevent the need for calculation of the wave height at the breaker line, it was decided to use the relationship proposed by Kamphuis and Readshaw (1978) and Readshaw (1979), namely:

$$K_p' = 0{,}7\,\xi_b \quad \text{for} \quad 0{,}4 < \xi_b < 1{,}4$$
$$(\text{say for} \quad \xi_b < 1{,}4)$$

$$1{,}24 \quad \textit{for} \quad \xi_b \geq 1{,}4$$

with $Q_s$ (kg/s) = $K_p' P_{ls} / 2g$

and S = $$\frac{31\ 557\ 600\ Q_s}{(1-p)\ \rho_s} \quad (m^3/yr)$$

where p = porosity of the sediment (assumed to be 0,4 for sand)
$\rho_s$ = density of the sediment (usually 2650 kg/m$^3$ for sand)
and 31 557 600 = number of seconds in one year

**Bailard** (1981) generalized the Bagnold (1963, 1966) energetics-based stream model. After integrating the local time-averaged longshore transport rate, Bailard (1984) obtained the following alternative equation for $K_1$, (called $K_3$) valid for both model and prototype applications:

$$K_3 = 0{,}05 + 2{,}6 \sin^2 2\theta_b + 0{,}007\ u_{mb} / w$$

where w = fall velocity of the sediment grains
$u_{mb}$ = $0{,}5\ \gamma\ (g\ d_b)^{0,5}$
and $\gamma$ = breaker index = 0,8

Bailard (1985) adds another term the equation for $K_3$ namely, 0,0096 tan $\alpha$. However, choosing a very high value of the beach slope (tan$\alpha$) of 0,2, it is clear that the estimated maximum value of this term is about 0,0019. For tan$\alpha$ = 0,04, a typical value, the term is only 0,00038. Because its contribution to $K_s$ is negligible, this term was omitted. Furthermore:

$$I = 0{,}5\ K_3\ P_{ls}$$

and S = $$\frac{31\ 557\ 600\ I}{(\rho_s - \rho)\ g\ (1 - p)} \quad (m^3/yr)$$

Watts (1953) empirically related the longshore transport rate to the wave energy flux factor. The **Watts formula** in SI units is:

$$S = 2223\ P_{ls}^{0,9}$$

Similarly, **Caldwell** (1956) obtained his **formula** (given here in SI units):

$$S = 2505\ P_{ls}^{0,8} \quad (m^3/yr)$$

## EVALUATION OF FORMULAE

### Method of Testing

The results of the testing of the formulae will be presented in a number of ways in order to facilitate interpretation. These are:

* A plot of the predicted longshore transport rates ($S_p$) versus the measured rates ($S_m$).
* The relative standard error of estimate ($\sigma$) was calculated (Kamphuis, *et al*, 1986):

$$\sigma = \Sigma_{i=1}^{n} \left[ \frac{(\log S_{p,i} - \log S_{m,i})^2}{n-1} \right]^{0,5}$$

where n = number of data points
i = number of the particular data point

* The discrepancy ratio ($r_d$) (Van Rijn, 1984) and its distribution were determined.

$r_{d,i} = S_{p,i} / S_{m,i}$

A histogram of the percentage occurrence versus $r_d$ gives this distribution.

(The residuals ($e_i = S_{m,i} - S_{p,i}$) were computed and plotted against $S_p$ to check whether there is a systematic trend in the residuals, or not - these are not shown. Refer to Schoonees (1994)).

### Results

Table 3 lists the relative standard error of estimate ($\sigma$) and the percentage occurrence of the discrepancy ration ($r_d$) within certain limits for the formulae. For example, the percentage of the predicted transport rates for which the discrepancy ratio falls between 0,5 and 2 or between 0,25 and 4 can be read from this table.

Figures 1 and 2 show the predicted longshore transport rates ($S_p$) versus the measured rates ($S_m$) for the SPM and the SPM, Kamphuis and Readshaw formulae respectively. The histogram of the discrepancy ratios for the SPM, Kamphuis and Readshaw formula is contained in Figure 3. Refer to Schoonees (1994) for similar figures of the other formulae. Note that in these figures m^3/yr means $m^3$/yr.

### Discussion

A first impression when examining Figures 1 and 2 and Table 3 is that considerable scatter exists in the predicted longshore transport rates. Based on this particular data set, the SPM, Kamphuis and Readshaw formula gives the best answer of the six formulae over the full range of measured longshore transport rates ($\sigma$=0,515; $r_d$ between 0,5 and 2: 65,0%). Even so this formula tends to underpredict high transport rates (Figure 2). This is an area of concern because at a particular site, most of the longshore transport occurs during a few storms so that it is important to predict high transport rates accurately.

It is interesting to note that the SPM formula, perhaps the best known and most used predictor, does not fare very well. Although one can argue that its poor performance at low transport rates (Figure 1) can be attributed to a lack of an incipient motion criterion, it is still clear that it over-predicts in the range 1,5 x $10^4$ $m^3$/year to 1,5 x $10^6$ $m^3$/year. What is, however, comforting is that for high transport rates (> 1,5 x $10^6$ $m^3$/year) the SPM predicts transport rates accurately. That is, for the few data points in this range. However, two of the oldest formulae, namely, the Caldwell and Watts methods, also do not have an incipient motion criterion but both appear to be more accurate than the SPM and the SPM and Swart formulae (compare $\sigma$=0,579 (Caldwell) and 0,685 (Watts) to 0,708 (SPM) and 0,720 (SPM and Swart)). In fact, adapting the SPM formula for grain size (SPM and Swart method) caused a slight decrease in the accuracy of the predictions. The similar answers of these two predictors can, however, merely indicate that most of the data points were collected for grain sizes between 0,2 mm to 0,4 mm as indeed found by Schoonees and Theron (1993). In this grain size range the SPM and Swart formula gives very similar answers to the SPM formula.

It is interesting to note that the original SPM, Kamphuis and Readshaw formula was only calibrated against laboratory data and therefore no field data of Data Set 1 were used in its derivation. The second-best formula (Caldwell's) only used a few of the data points, especially when compared to the 41 points of Data Set 1 included in the calibration of the SPM formula.

## FURTHER CALIBRATION OF THE SPM FORMULA

One can argue that the SPM formula is not applicable for coarse-grained sediment which are included in Data Set 1. In addition, the data points for which only S and $P_{ls}$ are available, should also be used.

Figure 4 shows the data in Data Set 2 with a distinction being made between fine - ($D_{50} < 1$ mm) and coarse-grained ($D_{50} > 1$ mm) sediment. It is clear from this figure that except for some minor overlap, two different populations of points are apparent. For the fine-grained sediment (206 data points) the best fit relationship is:

$$I = 0,20\ P_{ls} \qquad (1)$$
($R^2$ = coefficient of determination = 0,72)

Considerable scatter is evident. If the recommendation by Schoonees and Theron (1993) is followed whereby only data in their higher category (point rating 60% and better) is used (Tables 1 and 2), 46 data points are retained. Figure 5 illustrates the result while the equation is:

$$I = 0,41\ P_{ls} \qquad (R^2 = 0,77) \qquad (2)$$

or $I = 0{,}82\ P_{lr}$ (i.e. $K_r = 0{,}82$)

Unfortunately, the scatter is not significantly reduced and the range of $P_{ls}$ values is much smaller. In comparing Equations 1 and 2, it is clear that the elimination of the lower quality data, more than doubled the value of $K_s$. $K_r = 0{,}82$ is an increase of the value of 0,57 proposed by Komar (1988) based on 70 of the data points in Data Set 1. The value in the original formula is 0,78 which is derived from 41 data points (US Army, Corps of Engineers, 1984). Kraus *et al.* (1982) found K = 0,58 based on their data and those of Komar (1969), which are 25 data points. It would of course be even better to have site-specific calibration data before calculating longshore transport rates. The foregoing illustrates the great uncertainties involved in using the SPM formula and in view of this we recommend that the SPM, Kamphuis and Readshaw formula preferably be used.

Both Swart (1976) and Bruno *et al.* (1981) presented relationships between $K_s$ and $D_{50}$. Figure 6 shows these relationships together with the data having median grain sizes below or equal to 1 mm. From this figure it is clear that a single relationship between $K_s$ and $D_{50}$ will not explain all the scatter shown in Figures 4 and 6. The same applies if the settling velocity instead of the median grain size is used. Although this correlates with the finding of Komar (1988), the authors believe that a longshore transport formula must contain either $D_{50}$ or the settling velocity. It is also evident from Figure 6 that neither of the relationships by Swart and Bruno *et al* are generally valid. The relationship by Bruno *et al.* (1981) almost forms an upper envelope to the values.

Returning to Figure 4, a very approximate line through the coarse-grained sediment is:

$$I = 0{,}01\ P_{ls} \qquad (R^2 = 0{,}11) \tag{3}$$

Because of the considerable scatter in the data and the very low $R^2$, this equation should only be used to obtain a rough order of magnitude of the longshore transport rate. For these coarse-grained data as well, no single relationship between $K_s$ and $D_{50}$ (figure not shown) will explain all the scatter shown in Figure 4. Clearly, further work is required. For example, an incipient motion criterion (see e.g. Chadwick, 1989, Brampton and Motyka, 1984 and Van Hijum and Pilarczyk, 1982) is necessary.

## CONCLUSIONS

The data ranges of Data Sets 1 and 2 are quite wide and as such, cover most conditions encountered on natural beaches.

Of the six formulae (SPM formula and variations thereof), tested against Data Set 1, the SPM, Kamphuis and Readshaw method fared the best. The standard error of estimate for this method was 0,515 while 65,0% of the time, the discrepancy ratio ($r_d$) fell between 0,5 and 2.

By using only the data from Data Set 2 that fall in the higher (better) category of Schoonees and Theron (1993) - 46 data points -, the best fit relationship for sand ($D_{50}$ < 1 mm) is:

$$I = 0{,}41\ P_{ls} \qquad (R^2 = 0{,}77)$$

Unfortunately, significant scatter is still evident (Figure 5). It was also found that no single relationship between $K_s$ and the median grain size (or the settling velocity) will explain all the scatter in the data. In view of the uncertainties involved in using the SPM formula it is recommended that the SPM, Kamphuis and Readshaw formula preferably be used.

For coarse grained sediment ($D_{50}$ > 1 mm) 34 data points were available which yielded an approximate relationship:

$$I = 0{,}01\ P_{ls} \qquad (R^2 = 0{,}11)$$

Because of the considerable scatter evident in Figure 4 and very low $R^2$, this equation should only be used to obtain an order of magnitude of the transport. Again, no single relationship between $K_s$ and the median grain size (or settling velocity) will explain all the scatter in the data.

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**TABLE 1: DATA SET 1**

| Data set no. | Reference(s) | Location | No of points | Point rating (%) |
|---|---|---|---|---|
| 1 | Caldwell (1956) | Anaheim Bay California | 5 | 46 |
| 2 | Watts (1952) | South Lake Worth | 3 | 42 |
| 4 | Adachi *et al* (1959) | Miyazu Japan | 8 | 24 |
| 5 | Moore and Cole (1960) | Cape Thompson Alaska | 1 | 50 |
| 6 | Delorme (1981) | North & Central Africa | 5 | 49 |
| 8 | Sireyjol (1964) | Cotonou Benin | 1 | 51 |
| 9 | Castanho (1966) | Lobito Angola | 2 | 52 |
| 10 | Fairchild (1977) | Ventnor (NJ)<br>Nags Head (NC) | 2 | 36<br>37 |
| 12 | Bijker (1968) | Ivory Coast Abidjan | 1 | 19 |
| 13 | Komar and Inman (1970) | El Moreno & Silver Strand | 11 | 62 |
| 14 | Duane and James (1980) | Point Mugu California | 1 | 56 |
| 16 | Lee (1975) | Lake Michigan | 8 | 57 |
| 17 | Kana (1977) | Price Inlet South Carolina | 25 | 48 |
| 18 | Bruno *et al* (1981) | Channel Islands Harbour | 18 | 55, 67 |
| 21 | Inman *et al* (1980) | Torrey Pines California | 2 | 64 |
| 22 | Kana and Ward (1980) | Duck North Carolina | 2 | 57 |
| 23 | Gable (1981)<br>Dean *et al* (1982) | Leadbetter<br>Santa Barbara | 9 | 68 |
| 28 | Kooistra and Kamphuis (1984) | Pointe Sapin Canada | 2 | 60, 71 |
| 29 | Bodge (1986) | Duck North Carolina | 8 | 56,57,61 |
| 32 | Voitsekhovich (1986) | Ros. Pri. Kin. Black Sea | 39 | 58 |
| 33 | Chadwick (1989) | Shoreham Sussex England | 7 | 57,60 |

**TABLE 2: DATA SET 2**

Data Set 1 plus the following data:

| Data set no. | Reference(s) | Location | No of points | Point rating (%) |
|---|---|---|---|---|
| 3 | Ishihara *et al* (1958) | North Akashi<br>Miyazu | 10<br>7 | 37 |
| 7 | Sato (1962) | Fukue, Atsumi Japan | 5 | 61 |
| 11 | Sato and Tanaka (1966) | Port Kashima Japan | 2 | 58 |
| 15 | Hou *et al* (1980) | Taichung Harbour Taiwan | 4 | 57 |
| 19 | Chang and Wang (1978)<br>Wang and Chang (1978) | Santo Rosa Island (Bayside) | 35 | 55 |
| 20 | Knoth and Nummedal (1977) | North Bull Island | 5 | 52 |
| 24 | Dean *et al* (1987) | Rudee inlet Virginia | 3 | 63 |
| 25 | Nicholls and Wright (1991) | Southern England<br>H. Bury Long Beach<br>Hurst Castle Spit | 6 | 48 |
| 26 | Kraus *et al* (1982) | Shi. Hir. Aji. Oar. Japan | 12 | 63 |
| 30 | Laubscher *et al* (1989) | Richards Bay South Africa | 5 | 54 |
| 34 | Hou (1988) | Lin-Kou Northwest Taiwan | 1 | 58 |

**TABLE 3: RELATIVE STANDARD ERROR OF ESTIMATE ($\sigma$) AND PERCENTAGE OCCURRENCE OF THE DISCREPANCY RATIOS ($r_d$) FOR EACH FORMULA**

| NAME OF FORMULA | NUMBER OF DATA POINTS | $\sigma$ | PERCENTAGE OCCURRENCE OF $r_d$ BETWEEN: | |
|---|---|---|---|---|
| | | | 0,5 and 2 | 0,25 and 4 |
| SPM | 119 | 0,708 | 42,0 | 58,0 |
| SPM and Swart | 119 | 0,720 | 42,0 | 58,0 |
| SPM, Kamphuis and Readshaw | 123 | 0,515 | 65,0 | 95,1 |
| SPM and Bailard (bulk transport rate) | 119 | 0,741 | 46,2 | 66,7 |
| Watts | 123 | 0,685 | 42,2 | 65,0 |
| Caldwell | 123 | 0,579 | 56,1 | 75,6 |

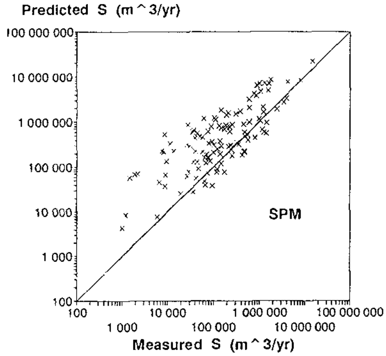


Figure 1: Predicted longshore transport rates versus measured rates for the SPM formula.

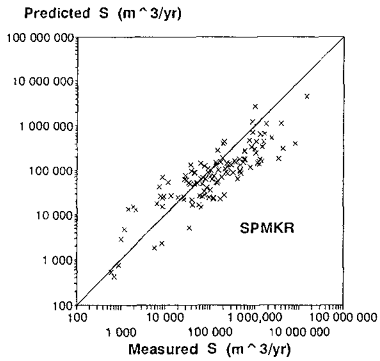


Figure 2: Predicted longshore transport rates versus measured rates for the SPM, Kamphuis and Readshaw formula.

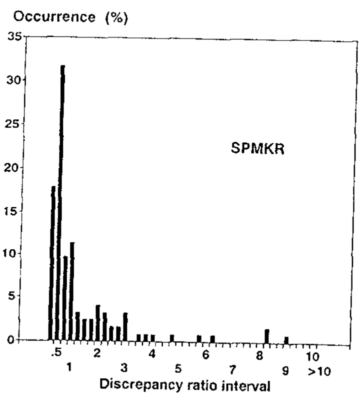


Figure 3: Histogram of the discrepancy ratios for the SPM, Kamphuis and Readshaw formula.

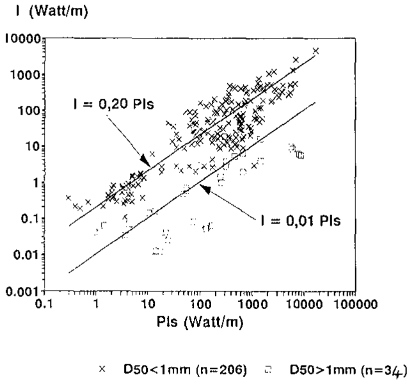


Figure 4: Immersed weight longshore transport rate (I) versus wave energy flux factor ($P_{ls}$) for Data Set 2.

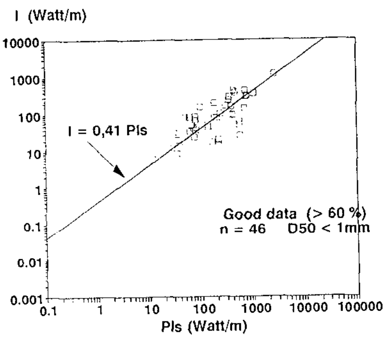


Figure 5: I versus $P_{ls}$, only for data with a point rating of 60% or more.

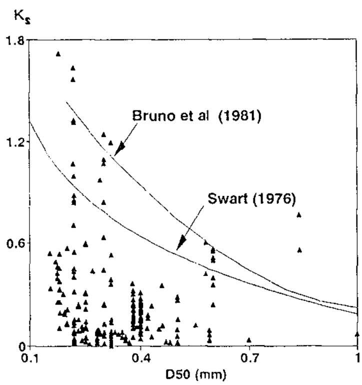


Figure 6: Coefficient ($K_s$) in $I = K_s P_{ls}$ versus median sediment diameter ($D_{50}$).