Evaluation of Longshore Sediment Transport Models on Coarse Grained Beaches Using Field Data: A Preliminary Investigation

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Abstract

This paper evaluates a number of widely used predictive transport equations and the use of tracers and GPS in the measurement of longshore transport for the validation of such equations. It also addresses the inconsistencies which can sometimes be introduced as a result of these techniques. The analysis shows that most of the equations examined tend to over-predict the expected transport by a factor of 1.5 to 4. The use of tracers on macro-tidal coarse grained beaches is found to be a viable method for obtaining reliable transport rate measurements of which the confidence levels are expected to increase as present day calculation techniques are adapted for use on macro-tidal shingle and mixed beaches. DGPS appears to be an economical way of data collection but needs to be used with the highest possible accuracy level settings if it is to be used in quantifiable sediment transport calculations.

Introduction

The management of beaches has become an important and effective engineering tool for protecting coastal areas. Increasing research efforts in this field have been aimed mostly at trying to understand and quantify the elements which govern the morphodynamics of beaches over both long- and short-term time scales. One of the key elements in improving the engineer's understanding of beach morphodynamics and sediment budgeting along a coastline is the search for a better determination of the net longshore movement of the sediment. The formulation of a reliable estimate of the total longshore transport (TLT) rate is paramount in coastal engineering problems such as feasibility studies of port extensions, derivation of

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sediment budgets for coastal areas and the appraisal of long term beach stability. Such estimates should be based only on the use of reliable sediment transport models underpinned by accurate transport measurements. To date, sand beaches have received the bulk of the attention. The number of documented studies and available data on sand beaches is, therefore, considerable and ranges from analytical/numerical models and laboratory tests to large scale field experiments. In strong contrast is the moderate attention which coarser grained (*i.e.* shingle) beaches have received. Studies of the processes governing shingle beaches have been limited mainly to empirical models based on laboratory studies, such as those by Pilarczyk and den Boer (1983) and Powell (1990). The prediction of longshore transport rates on shingle beaches has been mainly limited to the use of variations of the CERC formula from the US Army Corps of Engineers (1984), combined with laboratory studies.

Approximately one third of the UK's coastline is protected by shingle and mixed beaches (Fuller and Randall, 1988). Some of the areas protected by these beaches have a considerable economic importance attached to them. Coarser grained (*i.e.* shingle) beaches therefore warrant the attention of British researchers. The Shingle Beach Project (Van Wellen *et al.*, 1997) funded by the UK Ministry of Agriculture, Fisheries and Food (MAFF) and the Environment Agency (EA) was designed to go some way towards this. To date, two large scale field deployments have been carried out by the authors and their institutions in partnership with HR Wallingford. The 1996 deployment concentrated upon shingle transport on an open section of beach at Shoreham-by-Sea whilst the 1997 work was carried out on an adjacent groyned beach at Lancing. These two major field deployments have produced an extensive database of high quality field data. The present paper concentrates on the longshore transport rates as measured during the 1996 Shoreham open beach experiments and the evaluation of existing TLT equations using this field data.

Field Site

The field site at Shoreham-by-Sea, West Sussex, is an open stretch of beach consisting predominately of shingle. The beach is open towards the West and is in a natural state over an alongshore distance of 1500m. To the East, the beach is confined by a long harbour breakwater which extends approximately 200m. The prevailing wave direction is from the SW and SSW and the site is exposed fully to storm waves generated within the English Channel. A more detailed description of the field site is given in Van Wellen *et al.* (1997).

Historical Analysis of Net Longshore Transport and Annual Wave Climate

The Southern Water Authority (SWA) has been carrying out annual aerial surveys of the coastline in the area since 1973. The records also contain a statistical analysis of the trends of beach line movements and the changes in cross sectional area. In his analysis of this data, Chadwick (1989) assumed no longshore transport moving past the harbour breakwater. This assumption appears to be reasonable since the most seaward cross shore position of the toe of the shingle beach extends only half way along the breakwater. Chadwick estimated a mean sediment volume accretion of 14,539m^3 per year. This figure is supported by the volumes obtained from sediment bypassing around the harbour breakwater which suggest that sediment accumulates against the breakwater at a mean rate of 15,000-20,000m^3/a (Wilson, 1996).

The mean annual hydrodynamic conditions *i.e.* wave height, period, direction and frequency of occurrence within a representative year were obtained using hindcast offshore wave data based on a wind data set covering a four year period between May 1980 and August 1984 (Chadwick, 1991). This period is also covered by the SWA beach surveys, which increases the level of confidence with regards to the comparison of the predicted and measured transport rates.

Data Collection and Methods

One of the key objectives during the 1996 field work was to undertake a comprehensive series of field measurements of hydrodynamic conditions and concurrent sediment transport. This data has been used to evaluate the performance of existing analytical TLT equations and to make an intercomparison between independent techniques for measuring the longshore transport.

The first method of measuring the sediment transport at the field site was the use of tracers. Three types of shingle tracer were used within the project as a whole: painted indigenous pebbles (Caldwell, 1981); aluminium tracers (Wright *et al.*, 1978) and electronic tracers (Workman *et al.*, 1994). The comparatively low cost of the painted and aluminium tracers made them ideal for use in pilot studies in the early stages of the two deployments, when the least was known about the behaviour of the indigenous material and tracer losses were likely to be at a maximum. The highest quality tracer data (*i.e.* those studies with the highest recovery rates, the most frequent searches and the most complete supporting wave, current and sedimentological data) were those using the electronic tracer system. The main advantage of the electronic system was the ability to detect buried tracers at depths of up to 100cm as compared to 35-40cm with the aluminium system and 0-10cm with the painted tracers.

A wide range of tracer sizes and shapes were used within the study; the sieve diameters of the electronic tracers ranged from 23.9mm to 66.8mm and the shapes from 0.93 Maximum Projection Sphericity (MPS) to 0.621 MPS. These electronic tracers represent between 9.5 and 44.5% of the size range of the indigenous material. This is an advantage over the standard aluminium tracers which represented a smaller size and shape range throughout the majority of the study. The number of tracers deployed was relatively small (60-147) due to the labour intensive nature of tracer recovery and the logistical limitations of the study.

Tracer injection was at three cross-shore sites, chosen according to the expected active beach width at the time of deployment. Between 1 and 3 layers of tracers were placed at each cross-shore site to ensure that possible variations in tracer movement with depth were represented. The depths chosen were governed by the expected hydrodynamic conditions. The individually identifiable tracers were located by means of specially designed detectors and their depth and position surveyed in. Each of the electronic tracer studies lasted for four low waters in total. Tracer injection was carried out on the first low water, tracers were located but left in position during the two following low waters and were recovered on the fourth low water. Recovery rates of the electronic tracers lay usually around 90%.

From the tracer experiments, drift rates (Q_{ls}) were calculated using the method of Nicholls and Wright (1991) which has its basis in the work of Komar and Inman (1970). Three parameters are needed for this calculation: the velocity of movement of the tracer centroid (centre of mass) (U_s), the width of the active beach (m) and the thickness of the moving sediment layer (depth of disturbance) (n).

$$Q_{ls} = U_s m n \tag{1}$$

The recorded co-ordinates of the pebbles in the horizontal plane were used to calculate the tracer centroid (centre of mass) position on the beach. The velocity of the tracer centroid was given by the average longshore distance travelled by the moving tracers and the average duration of coverage. The average duration of tidal inundation of each tracer was determined by means of the height at which it was found on the beach and by using the measured beach profile data and Admiralty tidal predictions for the site. The thickness of the moving sediment layer was taken as the depth of the boundary between moving and non-moving tracers (Voulgaris *et al.*, 1998). If an event occurred in which more than 90% of the tracers were in transport, then the thickness of the moving sediment layer was taken as the depth above which 95% of the moving tracers were present. Active beach width was taken from the measured topographic profile at the site *i.e.* the distance between the high water mark and the sand/shingle border.

The second method of obtaining measurements of the transport rate is by means of calculating the volume changes of the beach based on topographic surveys in the vicinity of a structure (for example the harbour breakwater) which is assumed to stop all longshore transport. Traditional surveying allows constant high accuracy surveys to be carried out. However, using traditional surveying techniques, relatively few points can be captured over large areas within a short time period. Whilst the collection of a large number of points may not be relevant on simple topographic features, on more complex morphological surfaces there is a need for a system that can capture large amounts of data in relatively short time intervals. One answer to this problem is the use of DGPS (Differential Global Positioning Systems) to monitor beach morphological changes and the use of GPS technology is becoming more widespread by those concerned with obtaining and recording geographic information (Cornelius *et al.,* 1994). The most important features of GPS are its high positional accuracy and velocity determination in three dimensions, all weather capability, accurate timing capacity and global coverage (Leick, 1995). Importantly, from the point of view of the coastal geomorphologist, the ability of GPS kinematic surveying to record measurements rapidly and accurately over relatively large areas can be seen to be potentially invaluable in such a dynamic environment. Morton *et al.* (1993), discuss the use of GPS surveying techniques to monitor beach changes and state that GPS beach monitoring provides a way of understanding beach dynamics and the factors that influence volumetric gains and losses.

Typical surveys recorded between 3,500 and 5,000 points in a four hour time interval. These data points are then used as the input for a topographic modelling system to create a DEM (Digital Elevation Model) from the irregularly spaced data. This in turn allows subsequent volumetric analysis of the GPS data. For this purpose, individual blanking files for five different areas were set up (blanking files allow a particular section of the beach to be separated from a larger grid file). The volumetric differences were then fed into a finite difference scheme which allows calculation of

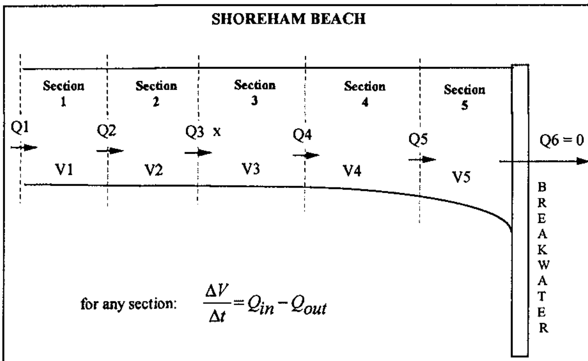

Figure 1 Schematic of finite difference scheme for the volumetric survey data.

the TLT rate tracer at the location where the tracer experiments took place (*x* on Figure 1).

The nearshore waves were recorded using the Inshore Wave Climate Monitor (IWCM; Chadwick *et al.*, 1995). This device consists of a star array of four 6m resistive sensors mounted on a 6m sided triangular aluminium tubular frame. This device measures the waves acting on the beach directly rather than measuring them offshore and having to refract them in by computational means at a later stage.

Sediment size distribution data were obtained from extensive sampling during the tracer experiments. Concurrently with each tracer experiment, sediment samples of approximately 70kg each were collected at each low water during a tracer study. Samples were taken at three cross shore positions close to the original injection sites for the tracers. The samples were then subjected to sieve analysis at half ϕ intervals.

Analytical Models Used

Numerous analytical expressions have been developed for the prediction of the TLT rate. A selection of seven equations representing the current approaches to longshore transport calculation is used here. They have been selected based on either their long standing use, their new approach to the analytical prediction of the TLT or the fact that they have been developed specifically for the transport of coarse grain material. The selected equations are:

- The energetics based CERC formula (CERC, 1984) calibrated for shingle size sediment comparable to that found during the field experiments (Chadwick, 1989)

CERCF
$$Q_{ls} = K\left(\frac{1+e}{\rho_s - \rho}\right)\left(\frac{1}{16}\rho g H_{sb}^2 C_{nb} \sin 2\theta_b\right) \quad (2)$$

where K is a proportionality coefficient equal to 0.0527, e is the void ratio, ρ is the fluid density, ρ_s is the sediment density, g is the gravitational acceleration, H_{sb} is the significant wave height at breaking, C_{nb} is the wave group velocity at breaking and θ_b is the angle of the breaker line relative to the shoreline.

- A physics based analytical equation for the longshore bedload transport ($Q_{b,ls}$) of shingle (Damgaard and Soulsby, 1996)

DS96
$$Q_{b,ls} = sign\{\theta_b\}\max\{|Q_{x1}|,|Q_{x2}|\} \quad (3)$$

where Q_{x1} is the longshore transport under current dominated conditions and Q_{x2} is the sediment transport under wave dominated conditions. Expressions for both of these can be found in Damgaard and Soulsby (1996). This equation explores a new path in analytical TLT prediction by means of using a force-balance approach to quantify the TLT rate.

- Two empirical formulae developed by Kamphuis (Kamphuis *et al.*, 1986 and Kamphuis 1991)

KAM86 $$Q_{ls} = \frac{1.28}{(1-n)(\rho_s - \rho)} \frac{\tan\alpha\, H_{sb}^{7/2}}{D} \sin 2\theta_b \tag{4}$$

where *tan* α is the representative bed slope, D is the representative grain diameter and n is the porosity. With additional laboratory study and further data analysis Kamphuis (1991) modified Equation (4) and included the influence of the peak wave period, T_p:

KAM91 $$Q_S = \frac{2.27}{(1-n)(\rho_S - \rho)} H_{sb}^2\, T_p^{1.5} \tan\alpha^{0.75} D^{-0.25} \sin^{0.6} 2\theta_b \tag{5}$$

This equation has been found to be the most accurate transport equation (Schoonees and Theron, 1996).

- Two improved versions of the Kamphuis 1991 equation as suggested by Schoonees and Theron (1996)

SCHA $$Q = \frac{63433}{365 \cdot 24 \cdot 60 \cdot 60} x_{Kamphuis} \tag{6}$$

recommended for use on exposed sites where the sediment is of a finer nature; and

SCHB $$Q = \frac{50000}{365 \cdot 24 \cdot 60 \cdot 60} x_{Kamphuis} \tag{7}$$

recommended for use at sites where calm conditions prevail and/or where the sediment is coarser.

$$x_{Kamphuis} = \frac{1}{(1-n)\rho_s} \frac{\rho}{T_p} L_0^{1.25} H_{sb}^2 (\tan\alpha)^{0.75} \left(\frac{1}{D_{50}}\right)^{0.25} (\sin 2\theta_b)^{0.6} \tag{8}$$

where L_0 is the deep water wave length.

- An empirical formula developed specifically for the transport of coarse grain material by van der Meer (1990)

VDM90 $$Q_{ls} = 0.0012 g D_{50} T_p H_{sb} \sqrt{\cos\theta_b} \left(\frac{H_{sb}\sqrt{\cos\theta_b}}{D_{50}} - 11 \right) \sin\theta_b \tag{9}$$

Evaluation and Findings

Using the long term average wave climate as input, the predicted TLT was calculated using the seven analytical models and compared to the expected net annual longshore transport. From Figure 2 it can be seen that CERCF and DS96 give the most accurate prediction for the sediment transport in the study area. This was not altogether unexpected since both of these equations have been calibrated against transport measurements for sediment of similar size to that at Shoreham beach. VDM90 scores rather poorly by giving the highest estimate of all despite being derived specifically for coarse gained sediment. KAM86 scores reasonably well and even out-performs the KAM91, which gives an estimate that is nearly three times as high as the one from KAM86. The improved versions of KAM91 (SCHA and SCHB)

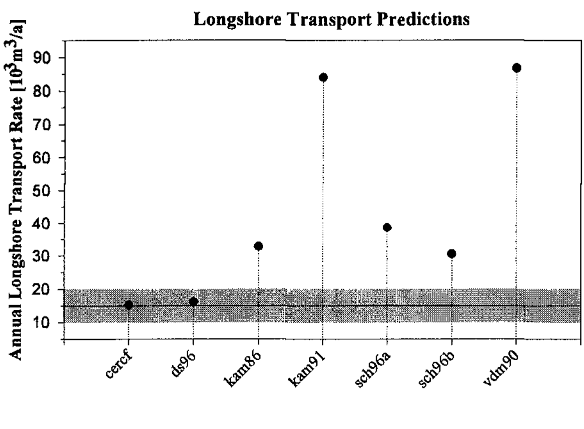

Figure 2 Expected (grey band) and predicted TLT at Shoreham.

give estimates which are closer to the one initially put forward by the KAM86 equation. Most equations appear to have a tendency to over-predict the TLT.

As part of the analysis, an extensive sensitivity analysis of the equations to the different parameters was undertaken. From this analysis two interesting plots are shown in Figure 3 and Figure 4. The TLT rates (Q) predicted by each equation have been divided by a reference TLT rate (Q_{ref}) obtained using that same equation with a fixed set of input parameters.

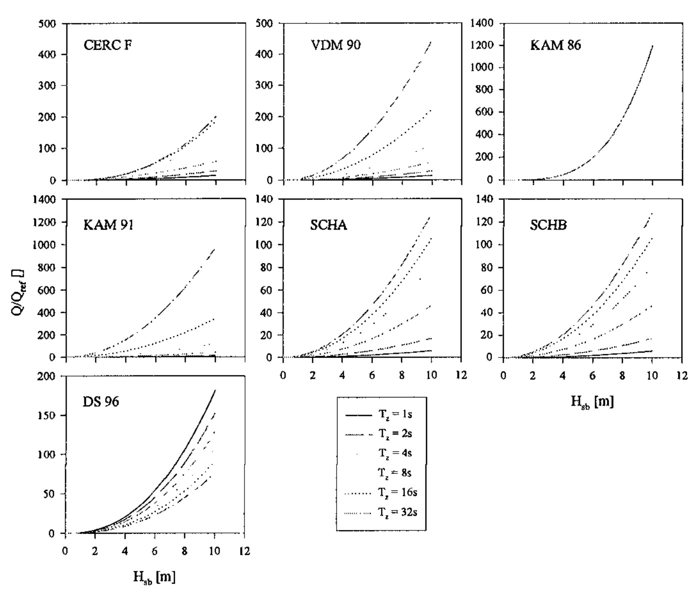

Figure 3 Sensitivity analysis for H_{sb}.

Figure 3 illustrates the power-law-like growth in predicted transport rate with an increase in wave height for each of the transport equations. The main difference is the magnitude with which the transport rate is increased. This is to be expected since all formulae incorporate the influence of the wave height on the transport by raising the wave height to a certain power larger than unity *e.g.* CERC-like equations have H^2. Apart from KAM 86 which does not take wave period into account, different transport rates are predicted for different wave periods. In general, all equations predict a larger TLT rate for larger wave periods. This appears to be a logical trend in transitional water depths were larger periods mean larger orbital velocities. Conversely, DS 96 shows an opposite trend, predicting larger transport rates for smaller wave periods. Since this equation assumes shallow water conditions the TLT becomes independent of the wave period but increases with wave steepness.

When looking at the influence of the D_{50} on the predicted transport rate (Figure 4) a similar anomaly is shown. Apart from the CERC equation (which does not take grain size into account) all equations predict lower transport rates for larger grain sizes. Again the exception is DS 96 which, under wave dominating conditions, predicts larger TLT rates for coarser sediment. This property of the DS 96 equation can be explained by the underlying assumptions of the model where an increase in D_{50} means an increase in the roughness influencing the wave boundary-layer and an increase in the wave related bottom shear stress resulting, in turn, in an increase in TLT (Damgaard and Soulsby, 1996).

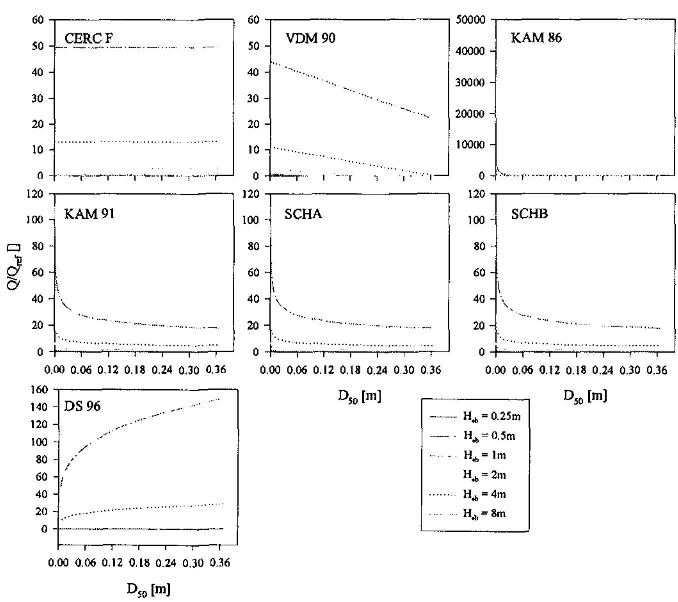

Figure 4 Sensitivity analysis for D_{50}.

With regard to sensitivity to θ_b, all the equations included in this paper showed a similar trend differing only in magnitude. Shoreham is characterised by a fairly stable wave climate with waves breaking at about 2 to 3° relative to the beach orthogonal and hence any variation in θ_b is unlikely to be an important factor in the comparison of measured and predicted TLT. Nevertheless, the sensitivity analysis showed the importance of an accurate determination of θ_b when predicting TLT.

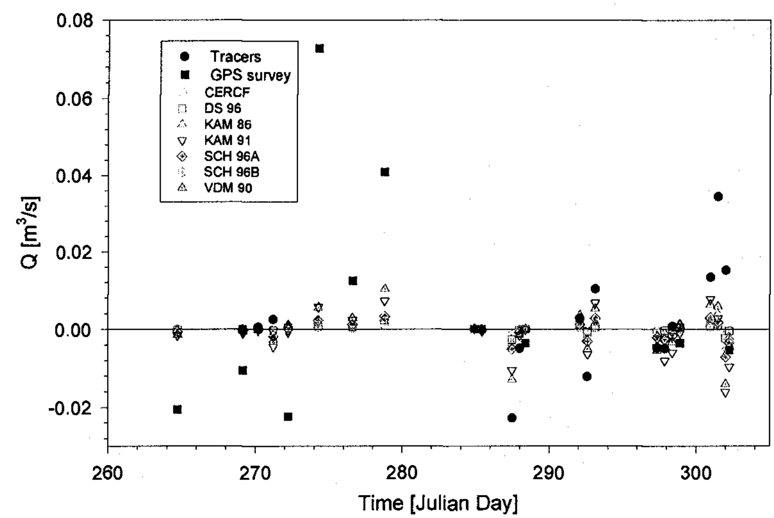

Figure 5 Measured (filled symbols) and modelled (open symbols) TLT for the 1996 fieldwork.

Using the wave data as recorded at the field site, Figure 5 shows a temporal plot of both the measured and the modelled TLT rates. It can be seen that there is a significant difference between the measured and the modelled rates.

To quantify the discrepancy between the measured and the predicted transport rates, a discrepancy ratio equal to $Q_{predicted}/Q_{measured}$ was introduced. Figure 6 and Figure 7 are histograms giving the percentage of occurrence that the discrepancy ratio from a certain formula can be placed in a preset interval. Combining these two figures with Figure 5, shows that for the tracer data most transport predictions made by the equations are characterised by a discrepancy ratio lower than 4 whilst for the GPS measurements nearly all fall in the bin for discrepancy ratios larger than 10. Since Figure 2 suggested that most models were likely to over-predict the transport measurements made during the experiment these discrepancy ratio's are likely to be underestimates. Calculation of the Relative Standard Error of Estimate (RSEE) for the GPS data suggests an average RSEE of about 1.4. This is a very high value and can be only partially explained by the relatively small sample size. Kamphuis (1986) and Schoonees and Theron (1996) using large samples, found RSEE values of below 0.4.

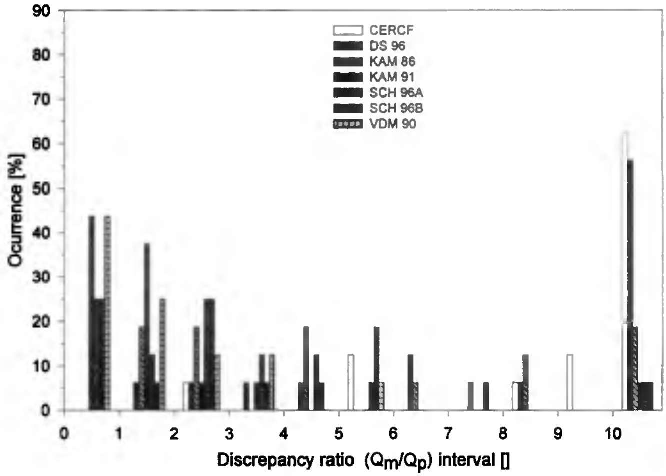

Figure 6 Discrepancy ratio of the predicted over the TLT rates measured by tracers.

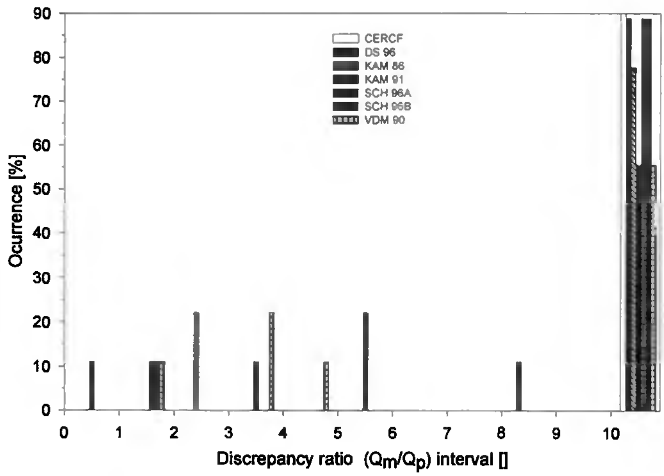

Figure 7 Discrepancy ratio of the predicted over the TLT rates measured by GPS.

One of the most widely accepted assumptions is that the TLT rate is proportional to the alongshore energy flux, *P*. The validity of this assumption has been underpinned by several studies and data sets (Kamphuis *et al.*, 1986, Kamphuis 1991 and Wang *et al.*, 1998). It is fair to say that this assumption holds true for shingle transport, although the importance of a threshold of motion criteria for sediment transport to occur is far greater than for sand. However, there is no consistent proportionality between the alongshore energy flux and the TLT rates measured by the tracers and GPS (Figure 8). The graph shows a significant amount of scatter and a particularly low correlation coefficient (r^2 = 52%) for the GPS measurements.

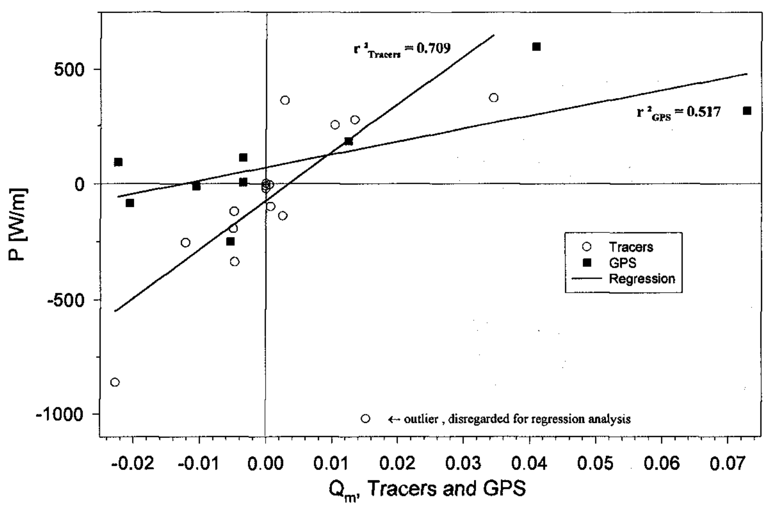

Figure 8 Correlation between the measured TLT rates (using Tracers & GPS) and the alongshore energy flux (P).

The significant difference in measured transport rates between the two systems was not expected, neither was the low correlation between the predicted transport rates and those obtained from the GPS measurements. The latter discrepancy is potentially more significant since GPS technology is starting to take over from the more classical surveying techniques in coastal management applications. Bodge and Kraus (1991) found their TLT estimates obtained from sediment impoundment combined with classic survey techniques to be more accurate than those obtained from tracer experiments. They stated that spurious trapping unrelated to the TLT and survey inaccuracies could each account for up to 100% of the TLT. Most of the erratic TLT measurements obtained from the GPS measurements are probably a result of the poor vertical accuracy accepted on the measurements made using the GPS when operating in kinematic mode in this study.

Some of the scatter in the data obtained from the tracers can be explained by the limitations of present day tracer theory. Often the main uncertainty lies in how representative the tracer is of the resident sediment, both in size distribution and quantity of the tracers. Bodge and Kraus (1991) stated that TLT estimates derived from tracers can be in error by a factor of 4 due purely to limitations in sampling methodology (or recovery rate, when dealing with individually identifiable tracers). However, problems such as recovery rates needed for reliable TLT measurements and differences in cross-shore distribution of the TLT have been minimised in this study by means of high recovery rates and by simultaneous injection of the tracer at different cross-shore locations. It is believed that the main uncertainty in the measured transport rate using the tracers is introduced through the calculation technique, which was originally developed for fine grain sediment on beaches characterised by a small tidal range.

Conclusions and Recommendations

This paper has examined a selection of today's most widely used predictive total longshore transport equations and two commonly used methods of obtaining estimates of the longshore transport under field conditions.

The CERC equation and Damgaard and Soulsby (1996) equation, calibrated for shingle of similar size to those found on Shoreham beach, appear to produce good estimates of the average annual TLT rate in the study area. The other equations tend to over-predict the expected annual TLT by a factor ranging from 1.5 to 4. This is perhaps not surprising since the Kamphuis equations and the Schoonees and Theron equations have been developed as general purpose transport equations rather than being specifically aimed at shingle and mixed sediment transport. The fact that they give predictions which are of the right order of magnitude gives a very encouraging signal for their future development to incorporate the coarser spectrum of the grain size scale, whilst maintaining their robustness by means of using only a limited number of environmental input parameters. The Damgaard and Soulsby equation shows promise in that it is based on the physically meaningful principle of force-balance. Unfortunately the resultant expression is significantly more complex. However, the sensitivity analysis has shown that it predicts opposite trends to all the other equations suggesting that further research is required. The van der Meer (1990) equation which was specifically developed for the prediction of TLT on gravel beaches did not perform well against the Shoreham long term transport data.

The use of tracers on macro-tidal shingle and mixed beaches shows promise in producing reliable transport rates. Care needs to be taken, however, since it appears that the present calculation techniques for obtaining sediment transport rates from the raw tracer data (*i.e.* the methods traditionally used for sand beaches and beaches with a small tidal range) may not be valid for the field conditions as described here. In general, the tracers appear to give higher transport rates than would be expected over the duration of a tracer experiment. This needs to be taken into account when extrapolating the results from tracer experiments to annual TLT values. Work is presently being undertaken within the MAFF Shingle Beach Project to improve the techniques for extracting transport rates from tracer data. It is expected that this will lead to an increase in confidence level on the measured values.

The method of obtaining estimates of the TLT rate from the volumetric change between topographic surveys using GPS was proven to be a fast and relatively inexpensive way of data collection. However, the potential error introduced by a low preset level in acceptable accuracy means that although more data points are collected, these do not necessarily give an accurate representation of the true beach volume. Ideally, real-time DGPS with a preset accuracy of 1cm in the vertical should be used if the data are to be used for construction of accurate morphological DEMs. This, in turn, will lead to a higher degree of confidence in the transport rates inferred from the changes in volume. This is especially important if the resultant transport rates are used by shoreline managers as part of a predictive tool over a wider range of time scales. Volumetric surveys, either from DGPS or more traditional methods using a Total Station or Level form a proven technique which should work irrespective of the type of beach or sediment. The fact that both short and long times between surveys can potentially smooth out the individual link between specific hydrodynamic conditions and the corresponding TLT but may lead to more stable predictions for the TLT.

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