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Intercomparison of research and practical sand transport models

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Abstract

A series of model intercomparisons, and model comparisons with field data, was carried out as part of the EU MASTIII SEDMOC Project (1998–2001). Initially, seven 'research' models were intercompared over a wide range of wave and current conditions, corresponding to both plane and rippled sand beds. These models included both one-dimensional vertical (1DV) formulations, varying in complexity from eddy viscosity and mixing length models to a full two-phase flow formulation, and also 2DV formulations capable of representing vortex shedding above sand ripples. The model results showed greatest convergence for cases involving plane beds, with predicted sand transport rates agreeing to well within an order of magnitude, and greatest divergence for cases involving rippled beds. A similar intercomparison involving (mainly) practical sand transport models, carried out over wide wave and current parameter ranges, also showed greatest variability in cases involving rippled beds. Finally, (mainly) practical models were compared with field data obtained at five contrasting field sites. The results showed that suspended sand concentrations in the bottom metre of the flow were predicted within a factor of 2 of the measured values in 13% to 48% of the cases considered, and within a factor of 10 in 70% to 83% of the cases, depending upon the model used. Estimates of the measured longshore component of suspended sand transport yielded agreement to within a factor of 2 in 22% to 66% of cases, and within a factor of 10 in 77% to 100% of cases. The results suggest that, at the present stage of research, considerable uncertainty should be expected if untuned models are used to make *absolute* predictions for field conditions. The availability of some measurements on site still appears to be a necessary requirement for high-accuracy sand transport predictions. However, for morphological modellers, the results may be viewed as more encouraging, since many of the present models exhibit agreement in their *relative* behaviour over wide ranges of wave and current conditions, which is a prerequisite to obtaining correct morphodynamic predictions. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The quantification of local sand transport rates in the marine coastal environment is a key element in the prediction of seabed changes, coastline evolution and

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the morphological impact of human interference in the coastal system. However, large gaps remain in our knowledge of sediment transport processes, and a continuing need exists for the development of reliable, well-validated, practical modelling systems. To this end, the EU MASTIII SEDMOC Project (1998–2001) ['*Sed*iment Transport *Mo*delling in Marine *C*oastal Environments'] brought together a group of coastal scientists and engineers to (i) assess the 'state-of-the-art' in the prediction of coastal sand transport rates, and (ii) fill some of the gaps in existing knowledge through experimentation and the development of improved models.

A specific objective of the SEDMOC Project was to "develop local sediment transport predictors, suitable for use in coastal sediment transport and morphological models, which achieve accuracy within a factor of 2 throughout the physical parameter ranges of importance in coastal engineering practice". [Here, 'factor of 2' means between 2 times and 0.5 times the actual transport.] With this criterion in mind, the present paper summarises a wide range of intercomparisons conducted during the SEDMOC Project. In an intercomparison with laboratory data in the earlier EU MASTII G8-M Project (see Davies et al., 1997), it was found that four different research models predicted net sediment transport rates beneath asymmetrical waves, and also in collinearly combined wave and current flows, to well within a factor of 2 of the measured values. In addition, cycle-mean sediment concentration profiles were predicted to good accuracy. However, the range of conditions investigated was quite narrow, involving sheet flow (i.e. plane beds) only.

In the present paper, the scope of the comparisons is considerably greater and, where comparisons are made with data, the emphasis shifts from the laboratory to the field. In Part I, seven 'research' models are intercompared over a wide range of wave and current conditions including both plane and rippled sand beds. In Part II, five 'practical' sand transport models, together with two of the 'research' models, are intercompared, again over a wide range of wave and current conditions. Finally, in Part III, one 'research' and four 'practical' models are compared with data obtained at several contrasting field sites. For a more detailed account of the respective comparisons, the reader is referred to Van Rijn et al. (2001).

The term 'research' model is used here to denote a model that represents many of the detailed physical processes involved in sand transport by waves and currents including intrawave transport processes. Such models are based on first principles, and are usually calibrated using empirical (e.g. turbulence) coefficients of a general kind. They tend to be developed for a particular transport regime (e.g. sheet flow above a plane bed), and they normally resolve the vertical structure (and also, in some cases, the horizontal structure) of the velocity and sediment concentration fields. Sand transport rates are then obtained by temporal- and spatial-averaging. By their nature, research models require lengthy computation times, and so they are not normally implemented in coastal morphological models involving many grid points.

In contrast, the term, 'practical' model is reserved here for simpler prediction schemes that either do not resolve the spatial and temporal structure of the velocity and concentration fields or, if they do so, employ simplified and prescriptive approaches for this purpose. Practical models have a more empirical character than research models, and generally have a longer development history involving adjustments, improvements and new calibrations, based on laboratory and field data. While such models are usually aimed at covering a wide range of conditions, they are sometimes limited to a particular type of problem (e.g. transport in the longshore direction only). By their nature, practical models are robust and easy to compute, and they can therefore be implemented relatively easily in coastal morphological models.

An important distinction between research and practical models is that, while research models determine both the 'wave-related' and 'current-related' components of the suspended load transport, practical models usually determine only the 'current-related' component. The respective components of the total sand transport rate are defined as follows. If the instantaneous velocity component (u), with which the sediment grains are assumed to be transported horizontally, and concentration (c), are written, respectively:

$$\underline{u} = \langle \underline{u} \rangle + \underline{u}_{\mathrm{p}} + \underline{u}' \quad \text{and} \quad c = \langle c \rangle + c_{\mathrm{p}} + c'$$

where both $\underline{u}$ and c are defined at height, z, above the bed; angle brackets denote averaging over a large (integral) number of wave periods; subscript p denotes the periodic component and a dash denotes the turbulent component, the cycle-averaged flux at level z is given approximately by:

$$\langle \underline{u}c\rangle \approx \langle \underline{u}\rangle\langle c\rangle + \langle \underline{u}_{\mathrm{p}}c_{\mathrm{p}}\rangle$$

where the small turbulent contribution $\langle \underline{u}' c' \rangle$ has been neglected. The net suspended flux, averaged over the depth from the reference level $z=a$ to the mean surface level $z=h$ is then given by:

$$\langle \underline{q}_{\mathrm{susp}}\rangle = \int_a^h \langle \underline{u}c\rangle \mathrm{d}z \approx \int_a^h [\langle \underline{u}\rangle\langle c\rangle + \langle \underline{u}_{\mathrm{p}}c_{\mathrm{p}}\rangle]\mathrm{d}z$$

in which the term $\langle \underline{u}\rangle\langle c\rangle$ gives rise to the 'current-related' contribution to the net transport, and the term $\langle \underline{u}_{\mathrm{p}}c_{\mathrm{p}}\rangle$ to the 'wave-related' contribution. Finally, the total net transport rate (S) is given by:

$$S = \langle \underline{q}_{\mathrm{susp}}\rangle + \langle \underline{q}_{\mathrm{bed}}\rangle$$

where $\langle \underline{q}_{\mathrm{bed}}\rangle$ corresponds to the net bed load transport in the height range $0<z<a$. Here, level $z=0$ usually represents the notional, undisturbed, (mean) bed level. However, if the sheet flow layer is taken into account explicitly in a model, the integration range may then involve levels below $z=0$.

The essential aim of the present paper is to give potential users of sediment transport rate formulae a quantitative assessment of the variability in the predictions of different formulations. Although some suggestions are made as to the likely causes of the differences between the predictions of the various models, it is not the present aim to discuss these causes exhaustively, not least because of the large number of models involved in the comparisons. The more limited aim is to give the reader an assessment of the uncertainty involved in working with models selected randomly 'off the shelf', and to emphasise the need both for an informed judgement about the optimum choice of model, and also for realism concerning the likely accuracy of sand transport computations. Although the discussion of the results is focussed primarily upon the differences between the *absolute* magnitudes of the transport rates and suspended concentrations predicted by the different models, some consideration is given also to the *relative* behaviour of the models. From the point of view of the morphological modeller, it is the correct general behaviour of a sediment transport model, over wide ranges of wave and current conditions, that is a prerequisite to obtaining reliable predictions of morphodynamic behaviour.

2. Part I. Intercomparison of research models

2.1. Introduction

The general aim was to make an assessment of a variety of research models, and to reach conclusions about the ability of these models to tackle sand transport problems involving wide ranges of wave and current conditions. The estimated transport rates were not verified against data, the present purpose being simply to quantify the absolute difference between the predictions of the various models. The approach adopted was to define a common set of input parameters that all the participating modellers could (as far as possible) use, thereby allowing the effect of the differences between model formulations to be highlighted. The task given to each modeller was to calculate the sediment flux, including the 'wave-related' component of the suspended load transport, for the defined conditions, and to present the results in a standard form.

Seven research models were intercompared for the defined ranges of wave and current conditions above a sand bed of uniform size. An overview of the models is given in Table 1. These numerical models either existed at the start of SEDMOC and/or were developed by the institutes named in the table during the project. The full details of the individual models are not given here; the reader is referred to the references cited in Table 1 for further information. Five of the research models were one-dimensional vertical (1DV) formulations; these varied in complexity from models based on eddy viscosity and mixing length assumptions to a full two-phase flow formulation. Two of the models were two-dimensional vertical (2DV) formulations based on turbulence-closure schemes, and capable of representing explicitly the process of vortex shedding above ripples in oscillatory flow. As might be expected, running these 2DV models, and also the two-phase model, in any given case represented a far more onerous task than that involved in running the simpler 1DV models.

Five of the seven models calculated both bed load and suspended load, and six of the models treated

Table 1
Overview of research models used in Part I

Model name [and institute]	Type, and turbulence-closure	Transport mode	Condition [and treatment of rippled beds]	Entrainment condition	β-factor ($=\varepsilon_s/\varepsilon_f$)	Turbulence damping included	Reference for details
'STP' [DHI]	1DV, eddy viscosity model	Bed load + Suspended load	Unsteady flow, mainly plane bed [Type 1]	Reference concentration (ZF94) + settling correction	$\beta=1$	No	Fredsøe et al. (1985)
'$K-\omega$' [DTU]	2DV, $K-\omega$ model	Bed load + Suspended load	Unsteady flow [Type 3]	Reference concentration (EF76)	$\beta=1$	No	Andersen and Fredsøe (1999)
'Two-Phase Flow' [LNHE/EDF]	1DV, $K-\varepsilon$ model in suspension layer	Bed load + Suspended load	Steady flow, plane bed only [Not Applicable]	Concentration continuous from stationary grain level	$\beta\neq 1$	Yes	Villaret et al. (2000)
'$K-L$' [IMAR]	1DV, $K-L$ model	Suspended load above z = 2D	Unsteady flow, mainly plane bed [Type 1]	Reference concentration (EF76) + settling correction	$\beta\neq 1$	Yes	Huynh Thanh et al. (1994) and Guizen and Silva (2000)
'$K-\varepsilon$' [SINTEF]	2DV, $K-\varepsilon$ model	Bed load + Suspended load	Unsteady flow [Type 3]	Reference concentration (EF76)	$\beta=1$	Yes	Brors (1999) and Utnes and Meling (1998)
'TKE' [UWB]	1DV, K-closure + similarity ℓ-scaling	Bed load + Suspended load	Unsteady flow, Plane or rippled bed [Type 2]	Reference concentration (EF76) + settling correction	$\beta=1$	Yes	Davies and Li (1997) and Davies and Villaret (2000)
'Mixing Length (l)' [UT]	1DV, mixing length (l)	Suspended load	Unsteady flow [Type 1]	Reference concentration (EF76 or ZF94) + settling correction	$\beta=1$	No	Ribberink and Al Salem (1995) and Dohmen-Janssen et al. (2001)

(1) Institutes: DHI = Danish Hydraulic Institute, DK; DTU = Technical University of Denmark, DK; LNHE/EDF = Laboratoire National d'Hydraulique et Environment, Electricité de France, FR; IMAR = Instituto do Mar, University of Coimbra, PT; SINTEF = Norwegian Hydro-technical Laboratory, NO; UWB = University of Wales, Bangor, UK; UT = University of Twente, NL.

(2) Treatment of rippled beds: 'Type 1': Standard plane bed modelling approach with enhanced bed roughness (k_s); 'Type 2': Two-layer model including eddy viscosity to represent ripple-related vortices; 'Type 3': Ripple-related vortices included explicitly in flow model in 2D vertical and horizontal domain.

(3) Reference concentration formulae: EF76 = Engelund and Fredsøe (1976); ZF94 = Zyserman and Fredsøe (1994).

both steady and unsteady flows. Phenomena associated with vertical velocity effects, such as boundary layer streaming, were absent in all cases. In most of the models, the (mean) motion of the sand grains in suspension was assumed to be identical to that of the fluid, apart from their settling velocity. Each model, apart from the two-phase model, utilised a time-varying reference concentration as the bottom boundary condition for the suspended sediment. In most cases the formula of Engelund and Fredsøe (1976) [EF76] was used, and in one case the formula of Zyserman and Fredsøe (1994) [ZF94] was used for the sediment concentration $c = c_a$ at the reference height $z = a = 2D$, where D is the median grain diameter. As discussed later, the implementation of these essentially flat-bed formulae in situations involving rippled beds probably gave rise to some of the discrepancies between the transport rates predicted by the different models. Although both of the above reference concentration formulae are based on steady flow considerations, they were applied here in an instantaneous, quasi-steady, manner, in response to the time-varying bed shear stress predicted by the respective models. The justification for this approach has been discussed by Davies et al. (1997). It may be added that, in most models, allowance was made for sediment settling by the implementation of a reference concentration which was the *maximum* of the two concentrations predicted instantaneously by (i) use of the EF76 or ZF94 formula; and (ii) the assumption of pure settling under gravity between the previous model time-step and the present one. This assumption, which was first used by Hagatun and Eidsvik (1986), makes some allowance for the dominance of sediment settling at certain phase instants in the wave cycle. The final information in Table 1 concerns the ratio (β) between the sediment diffusivity (ε_s) and the eddy viscosity (ε_f) in the present implementation of the respective models, and also whether some form of turbulent kinetic energy damping was assumed on account of vertical gradients in suspended sediment concentration. A more complete discussion of these concepts has been given by Davies et al. (1997).

2.2. The intercomparison task

The parameter settings for the task were similar to those used by Van Rijn (1993, Appendix A) to illustrate the practical model 'TRANSPOR'. The present comparison involved several currents alone, and four waves combined collinearly with these currents in water of depth 5 m, temperature 15° and salinity 0‰. Although collinear wave-current flows are less important in the coastal zone than flows in which the wave angle of attack on the current is large, the collinear case has been studied in many laboratory experiments and it allows the potentially significant wave-related component of the transport to be investigated. As indicated in Table 2, the depth-mean current velocity (U_c) varied in the range 0.1–2 ms^{-1}, and the four waves, referred to hereafter as 'Waves 1 to 4', were defined by their significant heights (H_s) and peak periods (T_p). Following the approach of Van Rijn (1993), the waves were treated as purely sinusoidal, and near-bed wave velocity amplitudes (U_w) were calculated using linear wave theory (without current dispersion) as 0.255, 0.568, 1.207 and 1.879 ms^{-1}, respectively. These values of velocity amplitude (U_w), rather than the wave height (H_s) and period, should be regarded as the given model inputs in the present exercise. The seabed sediment was assumed to comprise sand of single size D ($= D_{50}$) = 0.25 mm with geometric standard

Table 2
Inputs for the research model intercomparison

Current alone			
$H_s = 0$ m	$U_w = 0$ ms^{-1}		
Current + Waves 1 and 2		Current + Waves 3 and 4	
$H_s = 0.5$ m,		$H_s = 2.0$ m,	
T = 5 s:	$U_w = 0.255$ ms^{-1}	T = 7 s:	$U_w = 1.207$ ms^{-1}
$H_s = 1.0$ m,		$H_s = 3.0$ m,	
T = 6 s:	$U_w = 0.568$ ms^{-1}	T = 8 s:	$U_w = 1.879$ ms^{-1}
Depth-mean current velocity, U_c (m/s)	Bed roughness, k_s (m)	Depth-mean current velocity, U_c (m/s)	Bed roughness, k_s (m)
0.1	0.1	0.1	Flat bed
0.3	0.1	0.3	Flat bed
0.5	0.1	0.5	Flat bed
0.6	0.1	0.6	Flat bed
0.7	0.1	0.7	Flat bed
0.8	0.1	0.8	Flat bed
1.0	0.1	1.0	Flat bed
1.2	0.08	1.2	Flat bed
1.5	0.06	1.5	Flat bed
1.8	0.03	1.8	Flat bed
2.0	Flat bed	2.0	Flat bed

deviation of 1.0; thus, the settling velocity of the sediment in suspension was assumed to be the same as that of the bed material.

A key element in the present intercomparison was the specification of the bed roughness (k_s). In Van Rijn's (1993) original computations, values of k_s considered representative of field conditions were simply prescribed. Here, the same k_s-values were used for conditions in the *rippled-bed* regime; these situations correspond to the current alone, and the currents combined with Waves 1 and 2, apart from the strongest current ($U_c = 2$ ms^{-1}) which was considered sufficient to produce plane-bed conditions. In the rippled-bed cases, the prescribed roughness varied from $k_s = 0.1$ m (large ripple height) to 0.03 m (small ripple height), with the roughness decreasing as the current strength increased (see Table 2). For those models requiring ripple height as an input, this was to be set equal to the tabulated value of k_s. Moreover, if any model predicted the ripple height internally, this was to be replaced by the given value of k_s. If, additionally, any model required the ripple length, this was to be defined in relation to the ripple height. These considerations were particularly relevant to the 2DV models.

For Waves 3 and 4, the conditions were considered to correspond to the *plane-bed* (sheet flow) regime, whatever the strength of the current. In these cases (referred to as 'Flat bed' in Table 2), a standard granular roughness was prescribed, namely $k_s = 2.5D_{50} = 0.625$ mm. This choice is commonly made in models of the present kind (c.f. Davies et al., 1997). Moreover, by selecting the same k_s-formulation for all of the models, the set of inputs was made as rigid as possible, thereby focussing the intercomparison on the differences between the model formulations.

With these input conditions, each modeller was required to calculate total (including 'wave-related') sand transport rates as a function of depth-mean velocity and wave height. A total of 55 computations was needed to produce the required graph. In practice, not all of the models were suitable for running over the full wave and current parameter ranges. In these cases, an appropriate subset of the conditions was used. Complete coverage of the parameter range was achieved by 4 of the 7 models, and of these only three models (the 'K–L', 'TKE' and 'Mixing Length' models) complied fully with the task defined above. The following comments may be made about the remaining models:

2.2.1. 1DV STP model

This model was run for the current combined with Waves 1 to 4, but not for the current alone. Moreover, the STP model worked out, and used, its own (geometric) bed roughness for each case considered. For Waves 3 and 4, the bed was predicted to be plane, regardless of the current velocity, in accordance with Table 2. For Waves 1 and 2 combined with the stronger currents, the bed was also predicted to be plane. In all of these plane-bed cases, the geometric bed roughness was set equal to $k_s = 2.5D_{50}$. However for currents of strength less than about 1.5 ms^{-1} combined with Wave 2, and less than about 0.8 ms^{-1} combined with Wave 1, the bed was predicted to be rippled. The ripple dimensions were calculated using the empirical rules of Nielsen (1979), and the geometric roughness was then set equal to $k_s = 16\eta(\eta/\lambda)$ where η = ripple height and λ = ripple length. Thus, for rippled-bed cases, the bed roughness in the STP model was different from that used in the K–L, TKE and Mixing Length models.

2.2.2. 2DV K–ω model

This numerical model was run for only a limited number of cases in which the bed was considered/expected to comprise ripples of sufficient steepness to make model running interesting and useful. Thus, only five runs were carried out, involving the weaker currents combined with Wave 2.

2.2.3. 2DV K–ε model

Although similar considerations applied to this 2DV numerical model as to the K–ω model, it was run over rather wider parameter ranges including the currents alone, and the currents combined with Waves 1 and 2.

2.2.4. Two-Phase Flow model

The formulation of the Two-Phase model restricted it to steady flow only. Moreover, it was not possible to specify the bed roughness in this model, k_s necessarily being generated as part of the solution. For the current strengths simulated (U_c = 0.9, 1.0, 1.2, 1.5, 1.8 and 2.0 ms^{-1}), the bed roughnesses produced by the model were found to be k_s/D_{50} = 0.99, 1.51, 2.80, 4.65, 7.12

and 7.94, respectively. The successive increase in k_s with increasing current strength explains why, for the largest current strength, the transport predicted by the Two-Phase model differs from the rates predicted by the other models.

2.3. Results

Fig. 1a–e shows the results from the various models, firstly, for the current alone and, then, for the four combined wave and current cases. In each figure the calculated sediment transport rate (S) has been plotted as a function of the depth-averaged velocity U_c (11 values of U_c for each wave height H_s) on log–linear axes.

Considerable variability is evident in the results, most particularly for the current alone and for the current combined with Waves 1 and 2. This is due primarily to the differing treatment of the near-bed flow and reference concentration by the different modellers in rippled-bed conditions. For example, the 1DV TKE formulation included a near-bed, skin friction, submodel for cases in which the bed was rippled; in this submodel, the instantaneous bed load transport was computed using estimates of the skin friction component of the total stress, and the reference concentration was imposed at the required level ($z=2D$), even when this was below the level of no motion ($z=z_0=k_s/30$) defined in terms of the ripple roughness. The K–L and Mixing Length models did not include such a procedure, and this is likely to explain the smaller transport rates predicted by the TKE model. In addition, the K–L, TKE and Mixing Length models each predict smaller transport rates for the larger waves combined with some of the currents, and larger transport rates for the smaller waves combined with some of the currents. This is a manifestation of the 'self-regulating' nature of the seabed roughness, whereby rippled beds formed at low flow stages tend to enhance sediment transport, while plane beds formed at high flow stages tend to inhibit the transport.

In Fig. 1a–c, the transport rate drops between $U_c=1.8$ and 2.0 ms^{-1} according to most of the models. This effect, evident for the current alone and also for the current combined with Waves 1 and 2, is due entirely to the prescribed bed roughness, which falls sharply from $k_s=0.03$ m to 0.000625 m ($=2.5D_{50}$) as the current increases (see Table 2). As noted earlier, such a large change is probably physically unrealistic and, consequently, the predicted decrease in transport rate is also unrealistic. Nevertheless, the present calculations based on this roughness change are not without interest, as they show the behaviour of the respective models when confronted by a sudden change in roughness. For the reasons given earlier, the drop in transport rate does not occur for the Two-Phase Flow and STP models. In fact, the transport curves for the STP model all increase monotonically, even though the ripples were predicted to be washed out for the strongest currents.

Considering the individual plots in turn, Fig. 1a (Current Alone) shows significant variation in the predicted transport rates, particularly for current strengths in the middle of the U_c-range plotted. Not only are the absolute magnitudes of the transport rates significantly different, but the relative behaviour of the models is different as U_c increases. This is rather disturbing, since it might be expected that the case of a current alone would be the simplest one to simulate. The fact that this turns out not to be the case is due essentially to the differing treatment of the bed roughness in the respective models. The TKE and Two-Phase Flow models show the best agreement with each other, but this does not necessarily mean that they are making the most realistic predictions. In fact, the estimates given by both models are probably rather low. In the case of the Two-Phase model this is due to the fact that the model implicitly worked out its own value of the (granular) roughness k_s/D as part of each model run, and these values (stated earlier) were all considerably smaller than the prescribed values of k_s used for the rippled beds in the other models. In the case of the TKE model, the relatively low transport predictions were probably associated with an underprediction of the near-bed skin friction and, hence, the bed load transport rate. In contrast, in the centre of the mean velocity range, the K–L, Mixing Length and K–ε models predict much larger transport rates; here these models also exhibit similar general behaviour to one another. However, since the K–L and Mixing Length models take no account of skin friction effects in rippled-bed cases and simply impose the (unsteady) reference concentration at the level of no motion ($z=z_0=k_s/30$), it is likely that the resulting transport rates are overestimated. Only for

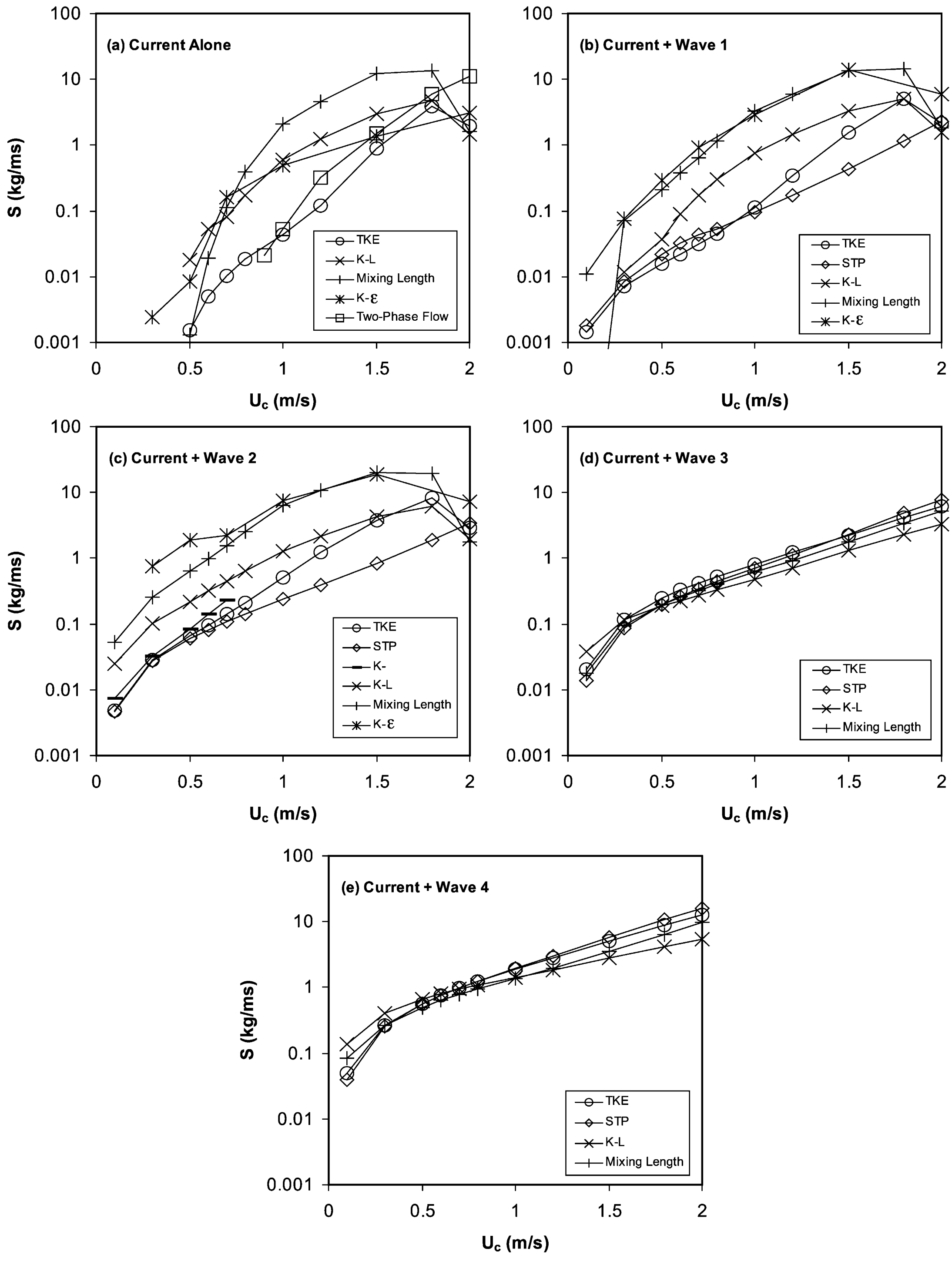

Fig. 1. Total net sand transport rates predicted by seven research models for (a) the Currents Alone, and (b) to (e) the currents combined collinearly with Waves 1 to 4.

relatively low ($U_c \approx 0.5$ ms^{-1}) and high ($U_c \approx 2.0$ ms^{-1}) mean velocities do the results from all five models converge on one another.

Similar patterns are evident in Fig. 1b (Current + Wave 1) and also Fig. 1c (Current + Wave 2). In Fig. 1b, rather larger transport predictions are now made by the Mixing Length and $K-\varepsilon$ models than by the $K-L$ model. In contrast, the smallest transport rates are predicted by the TKE and STP models, though it should be recalled that predicted (not prescribed) values of roughnesses were used in the STP model runs. In Fig. 1c, the relative behaviour of most of the models is more closely similar than in Fig. 1a and b. It is interesting to note that the 2DV $K-\omega$ model agrees rather well with both the TKE and STP models, in the range of low current strengths for which simulations were made with this model. However, for the lower current strengths, there is very little absolute agreement between these three models and the three remaining models ($K-L$, Mixing Length and $K-\varepsilon$); most striking is the lack of agreement between the two 2DV models, the $K-\varepsilon$ model predicting transport rates that are two orders of magnitude larger than those given by the $K-\omega$ model.

In Fig. 1d (Current + Wave 3) and Fig. 1e (Current + Wave 4), the bed was plane ($k_s = 2.5D_{50}$) and, consequently, the model results exhibit far better agreement, generally well within an order of magnitude. This is not unexpected since, in the earlier model intercomparison with laboratory data reported by Davies et al. (1997), it was found that four different research models (earlier versions of the STP, $K-L$, TKE and Mixing Length models) *each* predicted net sediment transport rates beneath asymmetrical waves, and also in collinearly combined wave and current flows, to well within a factor of 2 of the experimentally measured values on the basis of the assumption $k_s = 2.5D_{50}$. An interesting feature of the present results, particularly evident in Fig. 1e, is that more or less equal slopes are predicted for the transport-rate curves by three (STP, TKE, Mixing Length) of the four models, a rather smaller slope being predicted by the fourth ($K-L$) model.

2.4. Discussion

The aim of these comparisons has been to give the reader a general assessment of the variability in the predictions of different research models. Although it is not the present aim to try to explain all of this variability, the following observations may be made.

- In general, the model results show greatest convergence for cases involving plane beds, and greatest divergence for cases involving rippled beds. In the case of the plane beds, the bed roughness was defined as $k_s = 2.5D_{50}$, and the agreement between the models was well within an order of magnitude for all of the conditions simulated. In addition, the relative behaviour of the models was very similar. However, it should be added that, had the individual modellers been free to choose their own values of k_s in the plane-bed cases, there would probably have been less good agreement between the model results. For example, the use of a 'mobile' bed roughness (instead of $k_s = 2.5D_{50}$), which would have been the preferred choice of at least some modellers, would have increased transport rates by a factor of about 5. The fact that, in practice, the same bed roughness, and closely similar bottom boundary conditions for suspended sediment, were used in all of the models in the plane-bed cases (Fig. 1d and e) highlights the effect of the differing turbulence-closure schemes, which evidently produced variations by factors of between 2 and 5 in the predicted transport rates.
- The disagreement exhibited by the various models in the rippled-bed cases is substantial (by up to two orders of magnitude in some cases). Particularly disturbing is the fact that the two 2DV models showed such marked disagreement. The reason for this is not known, but may be connected with the different ripple shapes used in the respective models for the given bed roughness (k_s) (the choice of ripple shape having been left to the individual modeller). As far as the 1DV models are concerned, the differences in the results, for example, between the TKE and Mixing Length models, are due almost certainly to the differing treatment of the near-bed flow, and specifically of the height of implementation of the reference concentration. Differences between the various turbulence-closure schemes are unlikely to have accounted for the overall discrepancy in the absolute transport rates in these rippled-bed cases. In a relative sense, the behaviour of the models was rather different for the currents alone, but became more closely similar as the wave height increased.

3. Part II. Intercomparison of practical models

3.1. Introduction

A model intercomparison closely similar to that carried out in Part I was also undertaken for practical models. Again, the results were not verified against field or laboratory data. Instead, the purpose was simply to quantify the differences between the predictions when the various models were run over wave and current parameter ranges typical of conditions in the coastal zone.

Five ‘practical’ models were included in the present intercomparison. Of these, two were long-established formulations (‘BIJKER-A’ and Bagnold-Bailard [‘BB’]); one was an extended version of the formulation of Dibajnia and Watanabe (1992) [‘DW’] developed during the SEDMOC Project; and two were new models developed during SEDMOC, namely ‘SEDFLUX’ and TRANSPOR 2000 [hereafter ‘TRANSPOR’], an improved version of the TRANSPOR1993 model. Two further models were included in the present intercomparison, namely the 1DV STP and TKE models that were included as ‘research’ models in Part I. An overview of the practical models is given in Table 3. Again, the details of the individual models are not given here; the reader is referred to the references cited for further information. The table includes the name of the institute that provided the results for the comparison.

3.2. The intercomparison task

The task posed in the present intercomparison of practical models was exactly the same as that defined by Van Rijn (1993, Appendix A). The differences between the present task, and the task defined in Part I (see Table 1) were as follows.

- Although the same set of Currents and Waves (1 to 4) were used (in the same 55 combinations), the waves and currents were combined *perpendicularly* (not *collinearly* as in Part I). This corresponded to the typical situation of waves crossing a longshore current off a beach, allowing the modelling to be focussed on the current-related component of transport in the longshore direction.
- The bottom sediment was assumed to comprise a *mixture* of grain sizes defined by $D_{50} = 0.25$ mm and $D_{90} = 0.5$ mm. Hence, unlike the intercomparison in Part I in which only a single grain size ($D = 0.25$ mm) was assumed to be present, there was the potential here for the suspended grain size (D_s) to vary from run to run. In practice, as shown in Table 4, values of D_s smaller than D_{50} were prescribed for the Currents Alone and the currents combined with Waves 1 and 2, while D_s was assumed to equal D_{50} for the currents combined with Waves 3 and 4 in the more vigorous plane-bed cases. This reflects the fact that, while coarser grain fractions remain on the bed in relatively inactive conditions, all fractions of the bottom sediment can be entrained into suspension in more vigorous conditions.

Table 3
Overview of practical models used in Parts II and III

Model name [and institute]	Mode and rate of transport (bl = bed load) (sl = susp. load) (tl = total load) (mc = mean conc.) (w = wave-rel. tr.) (c = current-rel. tr.)	Type of bed forms/roughness (r = ripples) (f = flat bed)	Reference for details
BIJKER A: [DUT] B: [LNHE/EDF]	bl, sl, mc, c	r and f, A: k_s specified B: k_s predicted	Bijker (1971), Bijker (1992)
1DV ‘SEDFLUX’ [HR]	bl, sl, mc, c + w	r and f, k_s predicted	Damgaard et al. (1996, 2001a) Soulsby (1997)
Dibajnia-Watanabe (‘DW’) [IMAR]	tl, c + w	r and f, k_s predicted	Dibajnia and Watanabe (1992) Silva and Temperville (2000)
1DV ‘TRANSPOR’ [DH]	bl, sl, mc, c + w	r and f, k_s specified	Van Rijn (1993, 2000)
Bagnold-Bailard (‘BB’) [DH]	bl, sl, c + w	f, k_s specified	Bagnold (1966), Bailard (1981)

Note 1. Institutes: DH = Delft Hydraulics, NL; DUT = Delft University of Technology, NL; HR = Hydraulics Research Wallingford, UK; IMAR = Instituto do Mar, University of Coimbra, PT; LNHE/EDF = Laboratoire National d’Hydraulique et Environment, Electricité de France, FR.

Table 4
Inputs for the practical model intercomparison

Current alone			
$H_s = 0$ m			
Current + Waves 1 and 2		Current + Waves 3 and 4	
$H_s = 0.5$ m, $T_p = 5$ s:		$H_s = 2.0$ m, $T_p = 7$ s:	
$H_s = 1.0$ m, $T_p = 6$ s:		$H_s = 3.0$ m, $T_p = 8$ s:	
Depth-mean current velocity, U_c (m/s)	Suspended grain size (D_s) (mm)	Depth-mean current velocity, U_c (m/s)	Suspended grain size (D_s) (mm)
0.1	0.17	0.1	0.25
0.3	0.17	0.3	0.25
0.5	0.17	0.5	0.25
0.6	0.18	0.6	0.25
0.7	0.19	0.7	0.25
0.8	0.20	0.8	0.25
1.0	0.21	1.0	0.25
1.2	0.22	1.2	0.25
1.5	0.23	1.5	0.25
1.8	0.24	1.8	0.25
2.0	0.25	2.0	0.25

- The bed roughness was prescribed as indicated in Table 2, except that the roughness of the beds denoted as ‘Flat’ was taken here as $k_s = 0.02$ m, representative of field conditions. It might be argued that the granular roughness ($k_s = 2.5D_{50} = 0.625$ mm) commonly used for comparisons with laboratory data (and as used in Part I) should remain applicable for plane beds in the field. In practice, however, additional sources of turbulence may be assumed to be present in field conditions, for example, turbulence advected from upstream bed forms. The resulting increases in the bed shear stress and vertical mixing may be represented, albeit in an ad hoc practical manner, by enhancing the value of the bed roughness (k_s), as in the present comparison. Here, it should be added that, again, the STP model worked out its own values of k_s, with $k_s = 2.5D_{50}$ used for cases involving ‘Flat beds’.
- The waves were supposed to be irregular (JONSWAP spectrum). However each modeller was free to choose what representative wave height to use, for example, H_s or H_{rms}, depending upon the physics of the model and/or the “judgement” of the modeller.

3.3. Results

Although several of the models were capable of calculating the ‘wave-related’ component of the transport (in the cross-shore direction), only the ‘current-related’ component of suspended load transport was considered here. Thus, the total transport rate (S) discussed below comprised the sum of the bed load and current-related suspended load in the longshore direction. The calculated sediment transport rates are plotted in Fig. 2a to e, for the Currents Alone, and for the currents combined with Waves 1 to 4, respectively. Each model/formula was run/evaluated in all 55 cases, apart from the STP model, which was not run for the Currents Alone.

Most of the model results show a ‘logical’ trend, with the calculated sediment transport rate increasing with increasing current velocity. The feature of the results in Part I whereby the transport rate dropped (Fig. 1a–c) for the largest current strength is no longer present due to the substantially larger value of bed roughness (k_s) imposed in the present comparison. The difference between the model predictions varies between one and two orders of magnitude (factor of 10 to 100) over the 55 cases considered. The best absolute, and relative, agreement is found for the largest wave heights (Waves 3 and 4) and for the Currents Alone. Despite the general, relative, agreement between the models, even in the best of these cases the difference between the maximum and minimum calculated sediment transport rates still corresponds to a factor of between 10 and 30. The worst agreement is found for the intermediate wave heights (Waves 1 and 2). Here, although there is good relative agreement between the models, the factor between the maximum and minimum absolute values lies in the range 50 to 200. It should be emphasised that the ‘factor’ referred to here does not give information on the ‘true’ accuracy of the present models, since no experimental data was available to check the results. In practice, the discrepancy between the predictions of the models and the ‘true’ value may be much smaller, at least if the true value lies in the middle of the range of variability.

Closer inspection of the individual models reveals that, in general, the largest transport rates were predicted by the DW model. The DW model also predicted local maxima in the transport at $U_c = 1.5$ ms^{-1} for Waves 1 and 2. In contrast, relatively small

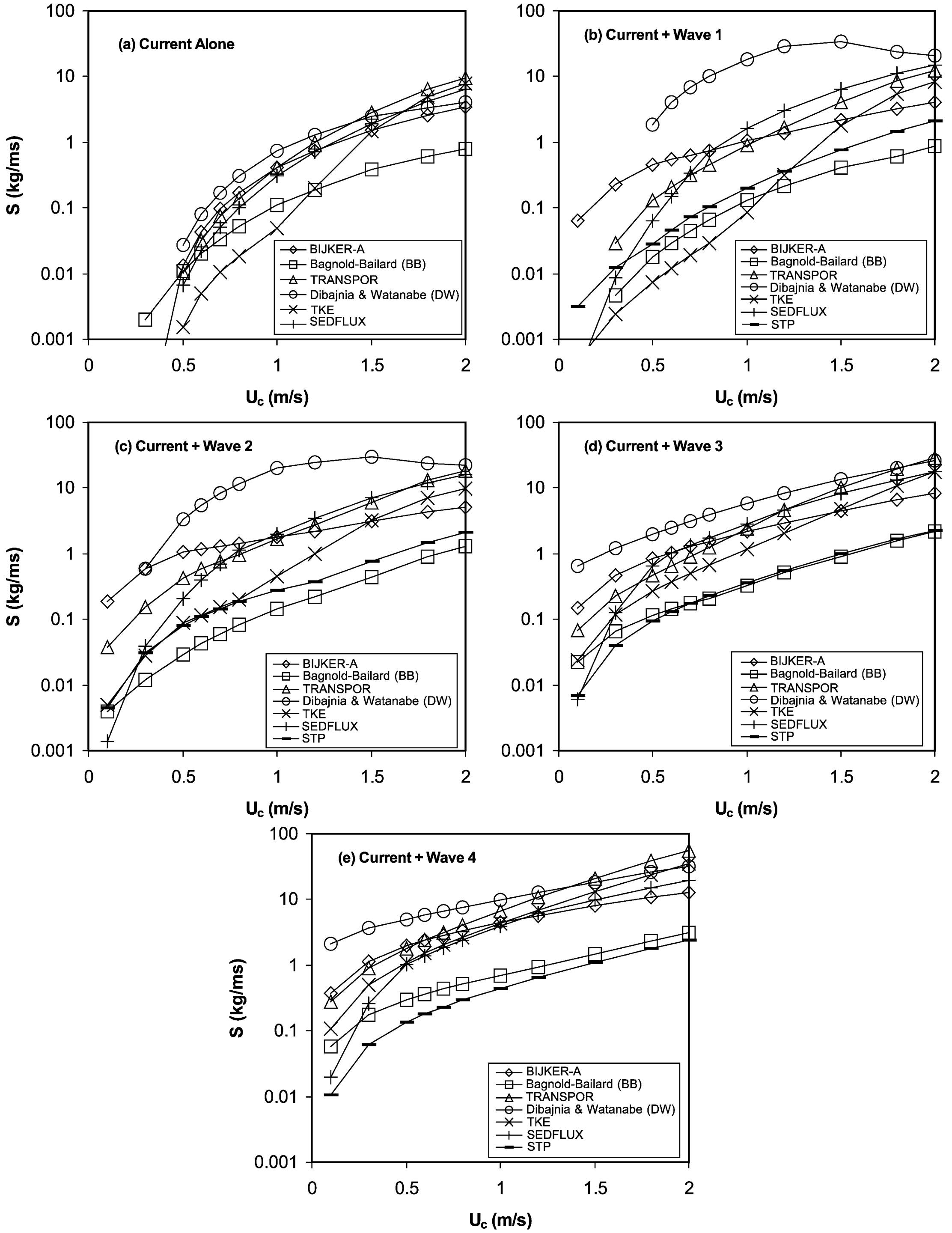

Fig. 2. Total net sand transport rates in the longshore direction predicted by five practical models and two research models for (a) the Currents Alone, and (b) to (e) the currents combined perpendicularly with Waves 1 to 4.

transport rates were predicted by the BB model. The same comment may be made about the STP model, though it should be recalled that this model calculated its own bed roughnesses. As far as the second research model (the TKE model) included in this comparison is concerned, this produced results comparable with most of the practical models for the stronger currents and larger waves, for which suspended load was the dominant transport mode. However, the TKE model predicted relatively low transport rates in the cases involving weaker currents and smaller waves, for which bed load was the dominant transport mode. The underlying reason for these low predictions of the bed load was the strict use by the model of skin friction concepts derived from laboratory work, which may have underestimated the skin friction, and hence the bed load, in the field conditions of present interest.

Of the remaining models, the practical models SEDFLUX and TRANSPOR show similar behaviour to one another, making predictions falling in the middle of the range of model variation in each case. Finally, the BIJKER (here, BIJKER-A) model produced broadly similar results, apart from two features. Firstly, the BIJKER model predicts a less rapid rate of

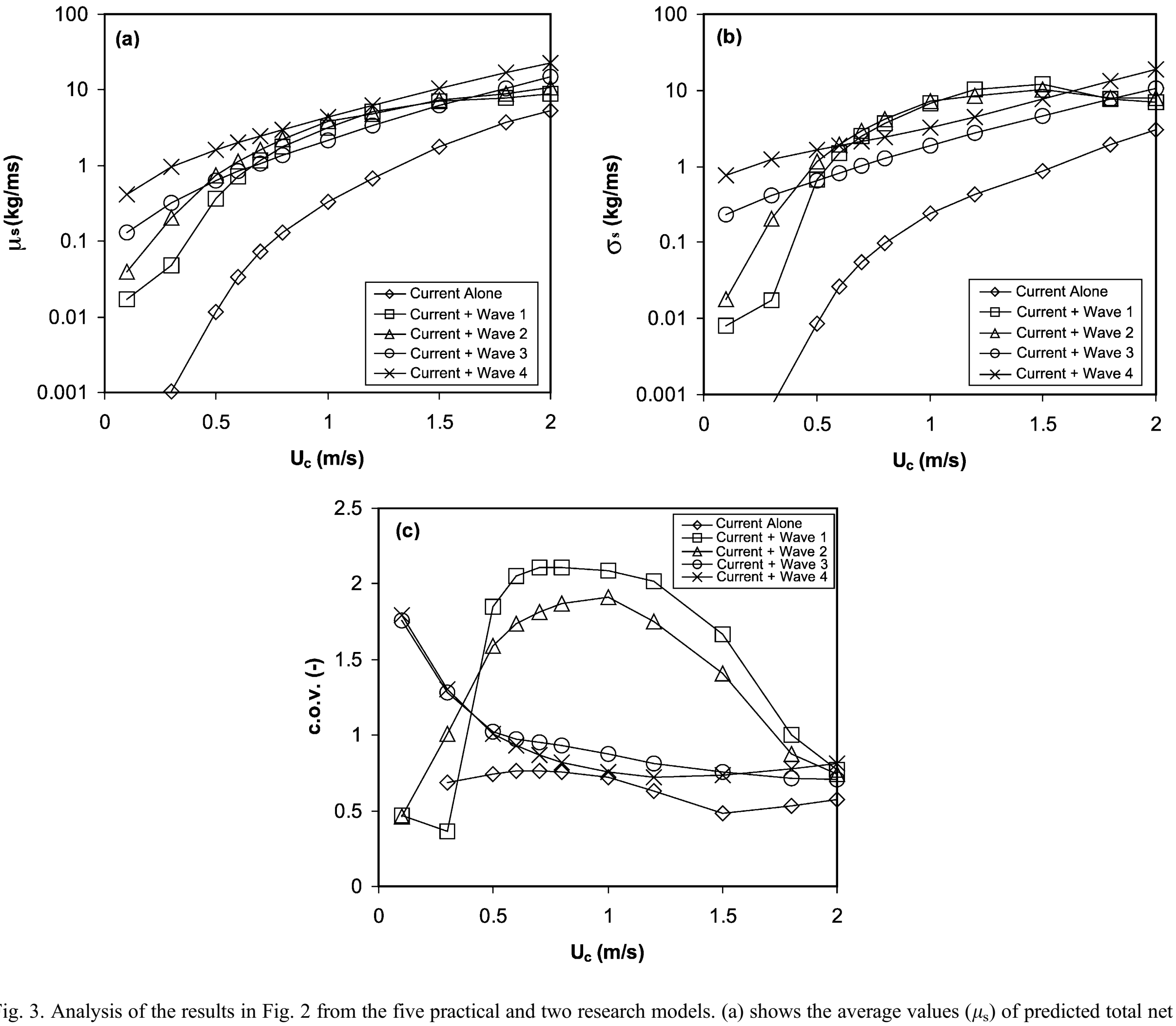

Fig. 3. Analysis of the results in Fig. 2 from the five practical and two research models. (a) shows the average values (μ_s) of predicted total net sand transport rate in the longshore direction; (b) and (c) show the corresponding values of standard deviation (σ_s) and coefficient of variation (σ_s/μ_s) based on the model predictions.

increase in transport as current strength increases than any of the other models (except perhaps DW) particularly for the smaller waves. Secondly, due to its highly nonlinear formulation for wave–current interaction, the BIJKER model predicts greatly enhanced transport rates, as soon as even low waves are superimposed on a current; this may be seen most clearly for the smaller current speeds in Fig. 2b and c (for Waves 1 and 2). These two features of the BIJKER model have been highlighted in a set of independent comparisons by Davies and Villaret (2000, 2002).

3.4. Assessment of differences between the practical models

In order to assess the differences between the model predictions, the average value (μ_S) and the standard deviation (σ_S) of the calculated sediment transport rates have been determined for each condition. Also, the coefficient of variation (c.o.v.), defined by σ_S/μ_S has been calculated. The latter is a measure of the relative standard deviation. These considerations are more appropriate in the context of the present intercomparison of practical models than for the comparison of research models in Part I, since the practical models have been calibrated, to a greater or lesser extent, using field data. These models may therefore be expected, a priori, to have the same underlying rationale, unlike the highly diverse research models that are based more on physical 'first principles' and involve little, if any, field calibration. [Although two research models (STP and TKE) are included in the present considerations, their effect on the values obtained for μ_S, σ_S and c.o.v. is broadly neutral.]

The results are plotted in Fig. 3a to c. Firstly, from Fig. 3a, it can be seen that the average sediment transport rate (based on the seven models) for a certain current velocity generally increases with wave height. However, there is some overlapping of the transport curves on account of the larger bed roughness (k_s) prescribed for Waves 1 and 2 than for Wave 3. Secondly, from Fig. 3a and b, it is apparent that the standard deviation (σ_S) has the same order of magnitude as the average (μ_S). However, more revealing information is given, thirdly, by the values of the c.o.v. Fig. 3c shows the lowest values of the c.o.v. for the highest current velocities. Here, the c.o.v. is about 0.75, meaning that the different model predictions agree rather well. Similar values for the c.o.v. are found for the Currents Alone and currents combined with Waves 3 and 4, for values of U_c between 0.5 ms^{-1} and 2 ms^{-1}. Here, the value of the c.o.v. varies between 0.5 and 1.0, again indicating good agreement. In contrast, the c.o.v. is maximum for Waves 1 and 2 for values of U_c between 0.5 and 1.5 ms^{-1}. Here, the c.o.v. values are equal to about 2. The value of the c.o.v. is, of course, determined to a large extent by extreme values and, for the Waves 1 and 2, the values predicted by the DW model deviate substantially from the other results. If these DW results are excluded, the c.ov. values reduce to between 0.4 and 1.0 over the entire range of conditions.

4. Part III. Intercomparison of models with field data

4.1. Introduction

At the start of the SEDMOC Project, a series of 'blind test' comparisons between field data and the predictions of various practical and research models was carried out. The philosophy underlying this exercise was not only to compare the computed results but also to examine the effect of different methods and model assumptions. The results of this initial intercomparison were reported by Damgaard et al. (1999). At the end of the SEDMOC project the exercise was repeated to demonstrate that the state-of-the-art had been advanced during the project. For brevity, we concentrate here only on the final outcome of the intercomparison, and refer the interested reader to Damgaard et al. (2001b) for a detailed account of the progress made during the project.

The models included in this intercomparison were the same as those used in Part II (Table 3), except that the STP model was not included, and the BIJKER-B model was used instead of BIJKER-A. BIJKER-B represents an extended formulation in which the bed roughness (k_s), rather than being prescribed, is calculated internally in the model using a ripple-prediction scheme (see Davies and Villaret, 2000, 2002). The modellers were asked to perform a set of specified sediment transport calculations corresponding to a variety of situations for which field data existed. The data was obtained at five field sites; these are discussed in two separate sections below. A slightly different subset of models was involved in the different comparison tasks.

4.2. Field test cases: Sites A to D

The modellers were given initially 36 sets of input data corresponding to field measurements obtained at four contrasting sites (Sites A and B in the UK, Site C in Belgium and Site D in the USA) with different hydrodynamic and sediment characteristics. The location and nature of the sites is summarised in Table 5, together with references giving more detailed information about the data. For all of these cases, measurements of suspended sand concentration were available, and it was therefore possible to validate as well as intercompare models. All of the data, except for some of those at Site B, were obtained outside the surf zone.

The idea of the comparison was that the modellers would be put into a situation similar to a consulting study, namely that 'blind' predictions were to be made corresponding to conditions on site and that, importantly, some information was *not* provided, leaving the modellers to make their own assumptions in order to perform the calculations. On the basis of the available information the following quantities were to be estimated:

- the sediment concentration at three defined heights above the bed for which (pumped sample) measurements existed (see Table 5);
- the magnitude and direction of the total sediment transport rate.

Further information about this comparison is given by Damgaard et al. (2001b). Here, details can be found concerning the inputs assumed or computed by the respective modellers, such as the bed roughness (k_s) and the suspended grain size (D_s) used in single-grain approaches.

4.3. Suspended sediment concentrations

The predicted concentrations at each of the three heights are plotted against the measured concentrations in Fig. 4. Four models were involved in this comparison (SEDFLUX, BIJKER-B, TKE and TRANSPOR). In the subplots corresponding to the respective models, the central 45° line represents perfect agreement, while

Table 5
Location and nature of the field sites A to D

Site	Hydrodynamics	Sediment	Number of tests	References
A: Maplin Sands, Outer Thames Estuary (UK)	Low, short period waves (H_s = 0.2–1.0 m, T_z = 2.0–3.3 s), strong tidal currents ($U_{1.00}$ = 0.0–0.8 ms^{-1}), water depths between 2.6 and 8 m.	Very fine sand D_{50} = 0.11 mm	18 with concentrations at 0.05, 0.1 and 1 m above bed	Whitehouse et al. (1996)
B: Boscombe Pier, Poole Bay(UK)	Long period large waves (H_s = 0.6–1.1 m, T_z = 6.5–7.9 s), weak currents ($U_{1.00}$ = 0.06–0.67 ms^{-1}), water depths between 4 and 5 m.	Fine sand D_{50} = 0.18 mm	7 with concentrations at 0.1, 0.5 and 1 m above bed	Whitehouse et al. (1997)
C: Middelkerke Bank (B)	Large storm waves (H_s = 2.7–2.9 m, T_z = 7.4–8.2 s), wind driven currents ($U_{0.76}$ = 0.2–0.5 ms^{-1}), water depths just over 20 m.	Coarse sand D_{50} = 0.45 mm	6 with concentrations at 0.05, 0.1 and 0.2 m above bed	Williams et al. (1997)
D: Duck, California (USA)	Large storm waves (H_s = 3.1–4.0 m, T_z = 10.2–12.1 s) and strong wind driven currents ($U_{0.29}$ = 0.2–0.4 ms^{-1}), water depths of 13 m.	Very fine sand D_{50} = 0.1 mm	5 with concentrations at 0.54, 0.87 and 1.2 m above bed	Madsen et al. (1993)

Note. T_z = zero up-crossing wave period; $U_{1.00}$, $U_{0.76}$, $U_{0.29}$ = mean velocity at height 1.00, 0.76 and 0.29 m above the bed, respectively.

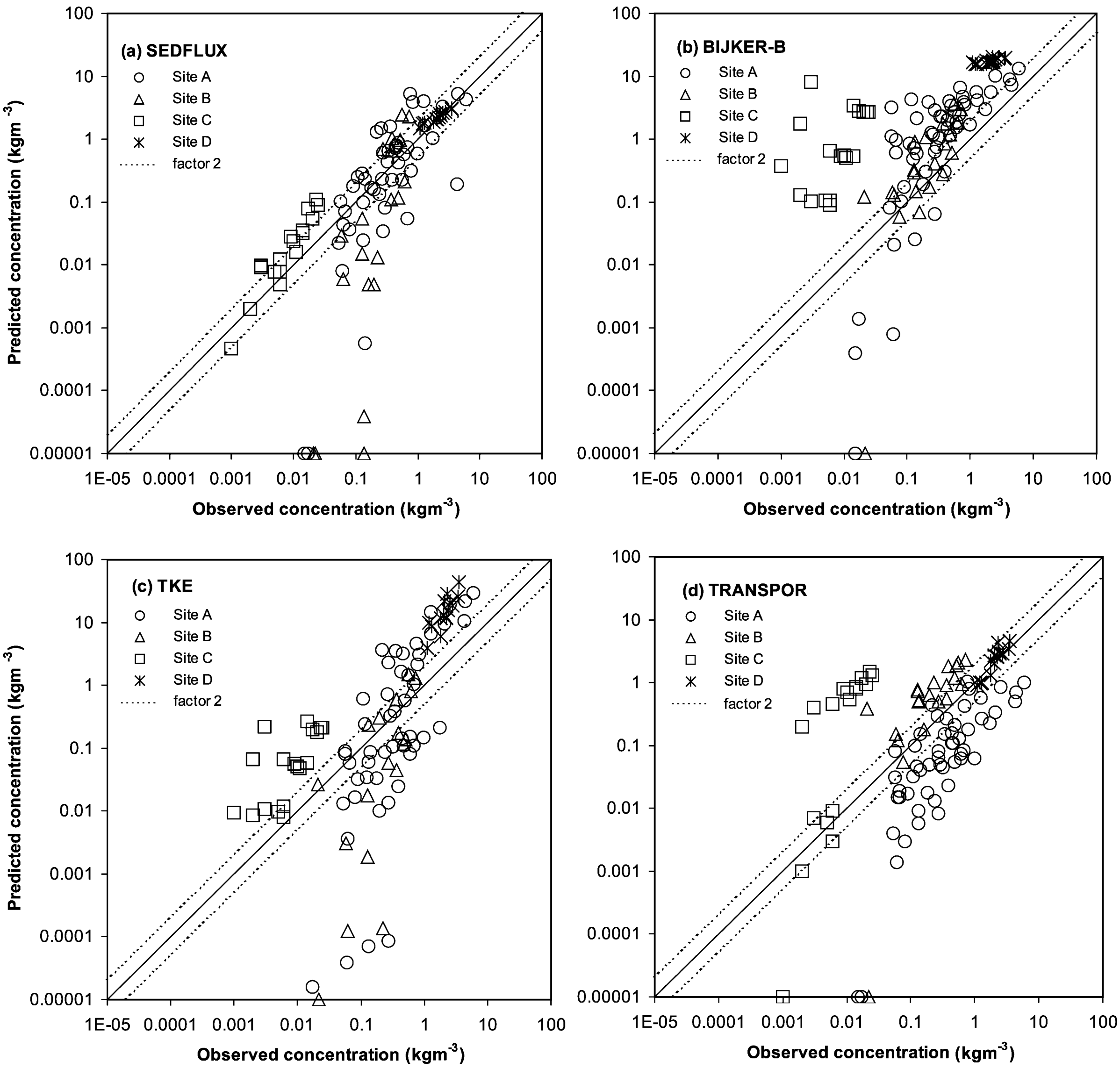

Fig. 4. Comparison between the observed and predicted suspended sediment concentrations at four field sites. The comparisons shown are for the following models: (a) SEDFLUX, (b) BIJKER-B, (c) TKE, (d) TRANSPOR.

the two adjacent 45° lines represent factor of 2 agreement. Any predictions of concentration with values lower than 10^{-5} kg m^{-3} were plotted as being equal to this minimum value, i.e. they were plotted along the x-axis. The different sites (A to D) are shown by the different plotting symbols. However, no distinction is made between the three heights at which the comparisons of concentration were made.

The overall level of agreement between the models and the observations is summarised in Table 6. Agreement within a factor of 2 was achieved in 13% to 48% of the 36 cases, depending upon the model used; agreement within a factor of 10 was achieved in 70% to 83% of the cases. The SEDFLUX model provided reasonable accuracy for low concentrations, though it underpredicted the lowest concentrations

Table 6
Summary of results for concentration predictions (Sites A to D)

Model name [and Institute]	Percentage of cases within a given agreement band		
	±2	±5	±10
'BIJKER-B' [LNHE/EDF]	13	45	70
1DV 'SEDFLUX' [HR]	48	76	83
1DV 'TRANSPOR' [DH]	31	62	75
1DV 'TKE' model [UWB]	15	45	72

(mostly for Site B); for high concentrations, it provided good accuracy (particularly for Site D). The BIJKER-B model tended to overpredict concentrations, particularly at Site C and for many cases at Site A, most probably because of overprediction of the bed roughness (k_s). The TKE model tended to overpredict high concentrations (Site D), and underpredict low concentrations (Site B). In practice, many of the underpredicted values corresponded to the uppermost height at which the comparisons of concentration were made. Finally, the TRANSPOR model gave reasonable overall agreement, tending to overpredict at Site C and underpredict at Site A.

Like the SEDFLUX model, the TRANSPOR model produced particularly good agreement for Site D. At this site, the conditions were such that all size fractions of the bottom sediment were capable of being entrained into suspension. However, this was not the case at all sites. At Site C, only 20–30% of the bottom sediment was capable of being suspended for the range of wave and current conditions considered; for Sites A and B the corresponding figures were 45–99% and 74–96% (all of these %-estimates coming from the TKE model solution). Of the present models, only SEDFLUX was run for multiple grain sizes (the TRANSPOR and TKE models, although also capable of this, were run here in single size mode only), and this may explain, particularly for Site C, why better results were obtained by SEDFLUX than the three other models.

The general tendency for all of the models to underpredict low concentrations is not surprising, and appears to be due in part to residual suspended sediment after slack water at low flow velocities. None of the models includes the background level of turbulence that tends to exist on site, and that appears to be necessary to explain this phenomenon.

4.4. Transport rates

The predicted total load transport rates are compared for the 36 cases in Fig. 5. Sites A, B, C and D correspond to Tests 1–18, 19–25, 26–31 and 32–36,

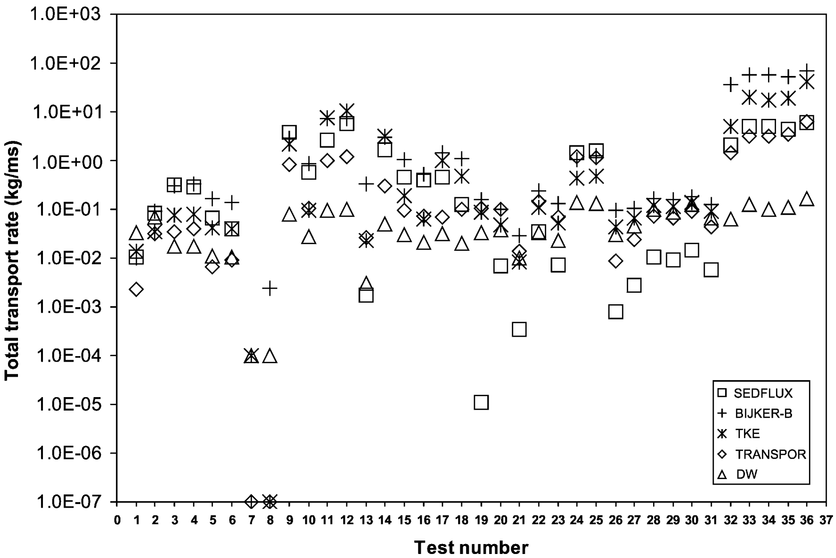

Fig. 5. Predictions of net sand transport rate for Sites A to D [Site A: tests 1–18; Site B: tests 19–25; Site C: tests 26–31; Site D: tests 32–36] from the following models: SEDFLUX, BIJKER-B, TKE, TRANSPOR, Dibajnia and Watanabe (DW).

respectively. Here, in addition to the four models discussed in the previous section, results from the DW model are also included. No field data was available for validation of the predicted transport rates.

It is immediately obvious that there is a large spread in the predictions, the five models differing by a factor of 5 at best and 10^4 at worst (though particularly large values of this order tend to reflect one or two outlying points). Typically, the spread in the predictions was over a factor of 100. In general, the transports predicted by BIJKER-B tended to be relatively large, and those of the DW model to be relatively small. For tests 32 to 36 (Site D), there is a clear separation of the values computed by the different methods; the lowest transports were predicted by the DW model and the largest by BIJKER-B. As noted above, at Site D all of the bottom sediment was capable of being entrained into suspension, making this a potentially easier site to simulate. However, despite the 'separation' of the predictions of the respective models at Site D, the general level of variation between the predictions is no less at Site D than for the three other sites at which only a proportion of the bed material was capable of being suspended.

4.5. Field test cases: Site E (Egmond)

The Egmond site is treated separately here on account of the rather different nature of the comparison undertaken compared with that for Sites A to D. The site is located in the central part of the Dutch North Sea coast and consists of a sandy beach (median sand size about 0.3 mm). Details of the general hydrodynamic conditions on site have been given by Kroon (1994) and Wolf (1997). Of particular relevance here were the measurements of instantaneous fluid velocity and time-averaged concentration at various levels above the bed (between 0.05 m and the water surface), which allowed the sediment transport rate to be estimated. Ten tests were considered in which estimates were made of the 'current-related' suspended transport rate in the longshore direction ($q_{s,long}$), defined as the depth-integral of the product of the time-averaged velocities and sand concentrations. The modellers were asked to compute this quantity given information about the significant wave height (H_s), the peak wave period (T_p), the mean water depth (h), the bottom sediment (defined by D_{50} and D_{90}), and the longshore and cross-shore components of the depth mean velocity (U_{long} and U_{cross}). The respective ranges of hydrodynamic conditions on site were $0.2 < H_s < 0.9$ m, $3.3 < T_p < 7.3$ s, $1.1 < h < 1.6$ m and $0.1 < U < 0.7$ ms^{-1}, where U is the resultant depth-mean velocity. Further information about this comparison is given by Damgaard et al. (2001b), where details can be found concerning the inputs assumed or computed by the respective modellers, such as the bed roughness (k_s) and suspended sand size (D_s) (for single grain models), neither of which was measured in the field.

The ratios of computed and measured longshore suspended transport rates are plotted in Fig. 6, and the percentage of these ratios falling within the factor of 2, 3 and 10 agreement bands is given in Table 7. Three of the models predict the transport rate to within a factor of 2 in more than half of the cases, and three of the models predict the transport within a factor of 10 in all of the cases. This may be considered to be an encouraging outcome.

The results in Fig. 6 have been plotted in terms of relative wave height (H_s/h), where H_s is the significant wave height and h is the mean water depth. There is a tendency for the ratio of predicted to measured transport to decrease with increasing H_s/h for each model. For $H_s/h \leq 0.25$ the bed was probably rippled, while for $H_s/h \geq 0.25$ the ripples were probably of low steepness and starting to become washed out. [Only in one of the nine cases was the ripple steepness predicted (by the TKE model) to be greater than 0.1]. In addition, for $H_s/h \geq 0.5$, spilling breakers were reported, providing an additional source of turbulence that was accounted for in only the SEDFLUX and TRANSPOR models. A factor of particular importance in the present comparisons was the suspended sediment grain size. According to the TKE model, between 36% and 83% of the sediment comprising the bed was capable of being entrained into suspension in the various tests. The way in which the respective models determined or represented the suspended grain size is likely to have had a significant effect on the results.

Against this background, the following comments may be made about the performance of the individual models. The TRANSPOR model produced generally

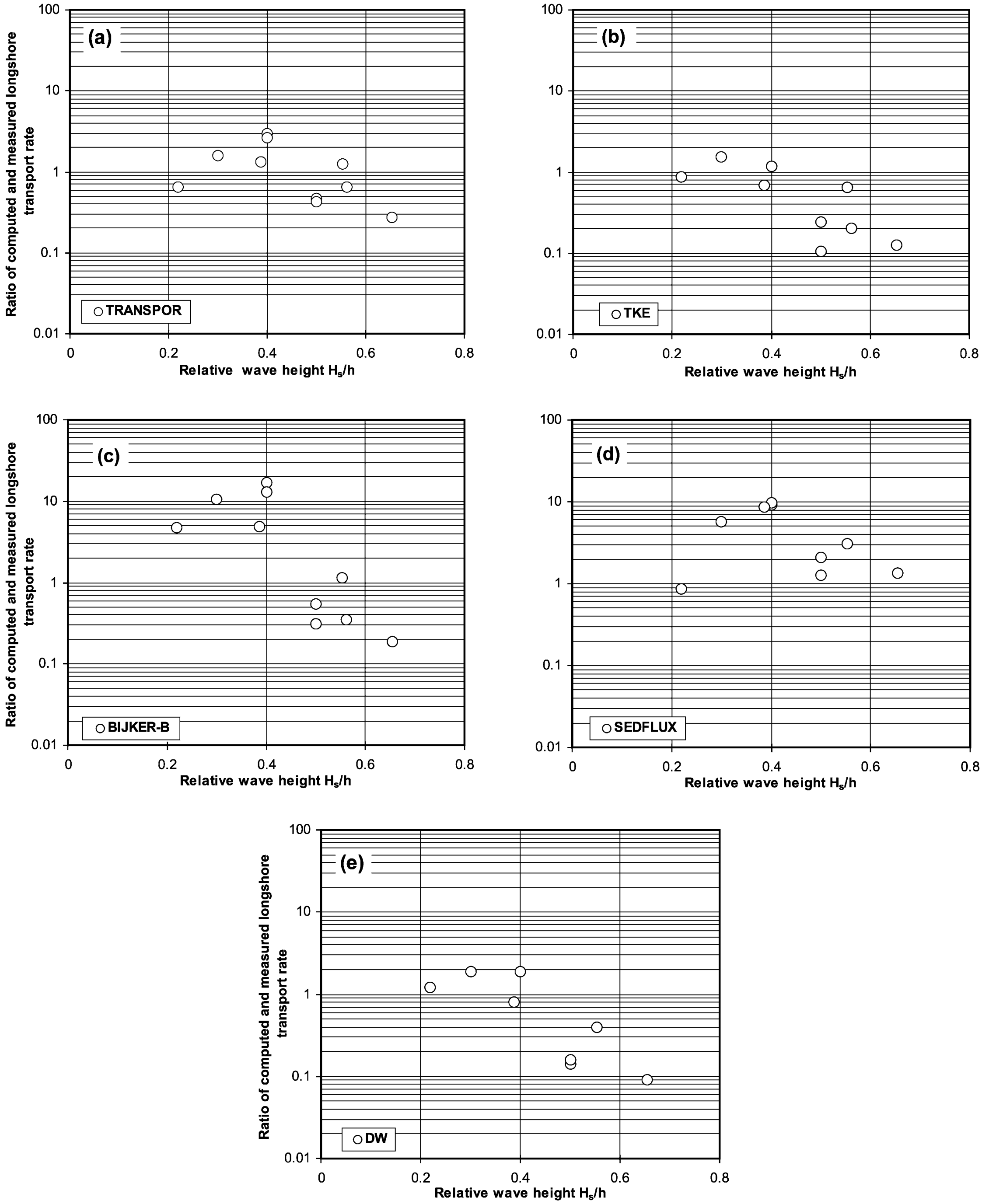

Fig. 6. Ratio of computed and measured longshore suspended sediment transport rates as a function of the relative wave height for the Egmond site. The comparisons shown are for the following models: (a) TRANSPOR, (b) TKE, (c) BIJKER-B, (d) SEDFLUX, (e) Dibajnia and Watanabe (DW).

Table 7
Summary of results for longshore suspended transport predictions at Site E

Model name [and Institute]	Percentage of cases within a given agreement band		
	±2	±3	±10
'BIJKER-B' [LNHE/EDF]	22	33	77
1DV 'SEDFLUX' [HR]	33	55	100
1DV 'TRANSPOR' [DH]	55	88	100
1DV 'TKE' model [UWB]	66	66	100
'DW' model [IMAR]	55	66	88

good predictions, though with a tendency for the transport ratio to decrease with increasing H_s/h. The same comment applies to the TKE and DW models, though in these cases the absence of any additional turbulence due to wave breaking led to a more marked underprediction of transport for large H_s/h. The BIJKER-B model tended to overpredict the transport for low H_s/h, and underpredict it for large H_s/h, to a greater extent than the other models. Finally, the SEDFLUX model produced good overall agreement, but tended to overpredict the transport for values of H_s/h ($\approx$ 0.4) in the middle of the range considered.

5. Conclusions

Model intercomparisons, and comparisons between model predictions and field data, have been made in order to assess the current state-of-the-art in (non-cohesive) sediment transport research. The comparisons reported here were carried out during the EU MASTIII SEDMOC Project (1998–2001).

Initially, seven 'research' models were intercompared over a wide range of wave and current conditions above a sand bed of given grain size. The models were of differing complexity including one-dimensional (1DV) and two-dimensional (2DV) turbulence models and also a two-phase flow formulation. A key element in the comparison was that the bed roughness (k_s) was specified, allowing the performance of the different models to be assessed for essentially the same input conditions. The results of the comparison showed that, in plane-bed cases (involving large waves and/or strong currents), the research models agreed to well within an order of magnitude, the differences between individual models being attributable to differences between the respective turbulence-closure schemes. In cases involving rippled beds (lower waves and weaker currents), the agreement between the models was less convincing, with predicted transport rates differing by up to two orders of magnitude in some cases. This disagreement is probably attributable to the rather different ways in which the bottom boundary condition for suspended sediment was implemented in the respective models.

A second intercomparison, carried out between five 'practical' sand transport models, showed a similar level of agreement between the predicted sand transport rates. For plane beds, the transport rates predicted by the models varied by a factor of between 10 and 30 in the individual cases. [This is somewhat higher than the equivalent variation found for the research models.] For the rippled beds, the variation was in the range 50 to 200.

A final set of comparisons was carried out between (mainly) practical sand transport models and field data obtained at a variety of sites with differing grain size characteristics. Here, the results showed that suspended sand concentrations in the bottom metre of the flow were predicted within a factor of 2 of the measured values in 13% to 48% of the cases considered, and within a factor of 10 in 70% to 83% of the cases. There was a tendency for low concentrations to be underpredicted, due probably to a residual amount of suspended sediment in quiescent conditions (e.g. near slack water) caused by turbulence not included in the model formulations. However, higher concentrations were predicted more convincingly. Use of a multiple grain size approach appeared to provide considerable advantages. As far as the prediction of sand transport rates is concerned, the present comparisons were rather encouraging. Estimates of the longshore (current-related) component of suspended sand transport made by five models yielded agreement within a factor of 2 of the measured values in 22% to 66% of cases, and within a factor of 10 in 77% to 100% of cases.

It should be emphasised that, in all of the present comparisons, *untuned* research and practical models were used. The research models discussed here tended to have been validated in laboratory conditions, and then adapted for field use, while the practical models were designed and calibrated for field use. It is not therefore surprising that the more sophisticated research models did no better in some of the comparisons than the relatively simple practical methods. Certainly, the research models produced results that appeared to be more volatile than those from the simpler practical approaches through the parameter ranges considered. This was probably due to the greater sensitivity of the research models to variations in the bed roughness (k_s). However, to view the present comparisons as a competition between research and practical models would be over-simplistic. While research models have been shown here to be capable of predicting transport rates at field scales as well as practical models, their true benefit lies in the diagnostic analysis that they make possible. The study of the detailed processes included in research models, of which the 'wave-related' component of suspended transport is an obvious example, is needed to improve our understanding of sediment transport phenomena. However, the difficulty in implementing research models necessarily mitigates against their use, paving the way for the use of practical models to provide an easy and fairly reliable means of estimating sediment transport rates.

The present paper has concentrated primarily on the differences between the absolute magnitudes of the transport rates predicted by different models, and on the differences between model predictions and field measurements of suspended concentrations and transport rates. Although such differences have been found to be substantial, it is important to note that it is not only the ability of models to make accurate *absolute* predictions that is important in sediment transport research. From the point of view of the morphological modeller, what is equally important, and possibly more so, is the *relative* behaviour of models. In particular, it is important that a transport model shows the correct behaviour i) as a function of the input parameters (waves, current and grain size) and ii) over a wide range of conditions involving several orders of magnitude in the transport rate. The correct behaviour of a transport model in this sense is a necessary condition for calibrating a morphological model and obtaining the correct morphodynamic behaviour. Since there is much more agreement in the relative behaviour of many of the models than in their ability to produce the same absolute magnitudes for the transport rate, the results of the present comparison could be viewed as rather encouraging from the point of view of morphological modellers.

Measurements of sand transport rates in the field are still rather sparse, making it difficult to validate sand transport models. However, from the comparisons presented here it may be concluded that the emphasis in future work should be directed towards improved models for *rippled*-bed conditions. These conditions are prevalent in offshore sandy regions on the continental shelf, and it is apparent that our understanding of these conditions is still rather limited. Specifically, there is a need for improved prediction methods for bed form dimensions and, hence, the bed roughness (k_s). The most difficult quantity to specify in some models is the bed roughness, which is usually not known from measurements. The specification of the roughness has a profound effect on results for the net sand transport rate, a relatively small change in k_s having a large effect on the computed transport. The procedures used here cannot be readily checked, as the sensitivity of sand transport in relation to bed roughness is normally unknown from observations. In contrast, in other models the bed roughness is not an input parameter, but an integrated part of the computation procedure; here also the correctness of the methods and procedures involved is often uncertain.

Finally, it is clear from the present comparisons that, if a user selects a research or practical model randomly 'off the shelf', and then uses it in an untuned manner to make predictions for field conditions, considerable uncertainty is to be expected. Evidently, the state-of-the-art in sand transport research still requires some knowledge of conditions on site, allowing the user to carry out model validation and/or tuning and, hence, make an informed judgement about the optimum choice of model for use in sand transport computations. At the present stage of research the availability of some field measurements is a necessary requirement for higher accuracy predictions.

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