Proudman Oceanographic Laboratory

PROMISE Literature Review on Turbulence, Wave and Suspended Matter Transport Modelling

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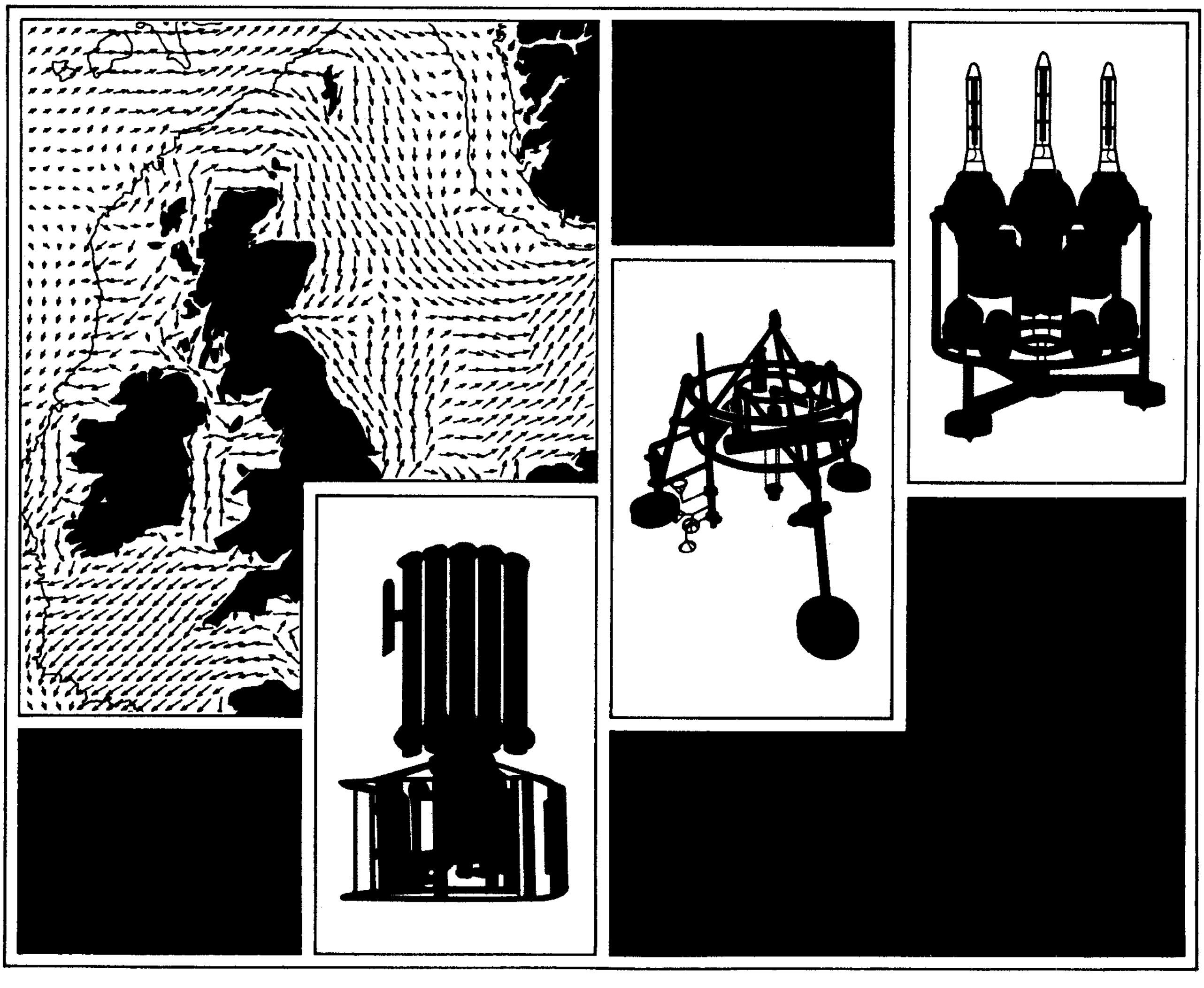

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PROMISE LITERATURE REVIEW ON TURBULENCE, WAVE AND SUSPENDED MATTER TRANSPORT MODELLING

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ABSTRACT

The objective of the MAST 3 project 'PROMISE' is to develop a framework to optimize the application of existing pre-operational dynamical models of the North Sea. The application concentrates on quantifying the rates and scales of exchange of sediment between the coast and the near-shore zone. The methodology will enable subsequent application of this framework to other coastal areas and for broader management applications.

Within the framework of PROMISE, this review has been performed to give an overview of the state of the art in modelling the transport of suspended matter including the effects of waves and turbulence; thereby supporting the participants with a common database. It is based on the contributions of the participants thus cataloguing the tools used within the PROMISE project.

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Contents

1. Turbulent Flow

The starting point to address turbulent flow investigation is the Navier-Stokes equations and the accompanying scalar (thermal) transport equations. These equations describe all the details of the turbulent fluctuating motions but these details cannot presently be resolved by a numerical calculation procedure. As all these details are in general of minor interest, the amount of information may be reduced by statistical methods considering only mean quantities. This approach was first suggested by Osborne Reynolds [4]. Mean quantities are defined as:

$$\bar{U} = \frac{1}{T} \int_0^T \tilde{U} \, dt$$

Equations for these average quantities can be derived formally by separating the instantaneous values of the various quantities into mean and fluctuating values: $\tilde{U} = \bar{U} + u'$. The averaging of the Navier-Stokes equation eliminates all fluctuations from the linear terms so only the influence from non-linear interaction terms are retained. The extra terms $-\overline{u'_i u'_j}$ are the so-called *Reynolds stresses*, which describe the influence on the mean flow from the exchanges of fluid by velocity fluctuations (see e.g. Petersen 1992 [82]).

1.1 Turbulence Models

The task of any turbulence model is to represent the correlations in the mean-flow equations in a way which closes these equations by relating the correlations to the averaged dependent variables. Trying to derive equations for the correlations themselves directly from the Navier-Stokes equation leads to new unknown correlations of one order higher. This problem (often referred to as the "closure problem" in turbulence) makes it necessary to close the equations in other ways. Hypotheses must be introduced for the behaviour of these correlations which are based on empirical information; hence turbulence models always contain empirical constants and functions.

One generally accepted understanding of turbulence is the existence of a large number of intermingled eddies with different velocities and sizes. A quantitative description of these velocity fluctuations can be given by the turbulence spectrum. The simplest description of this spectrum uses two parameters: a velocity scale defined by the amplitude of the most energetic velocity fluctuations, and a length-scale given by the location in wave-number space of the large eddies. A parameter used in many turbulence models is the eddy viscosity ν_t, which was introduced by Boussinesq assuming, in analogy to the viscous stresses in laminar flow, that turbulent stresses are proportional to mean-velocity gradients (ASCE [4]) (mean strain-rate, see Petersen 1992 [82]). Then the six unknown Reynolds stresses are reduced to one unknown parameter, the eddy-viscosity ν_t. Eddy viscosity is in contrast to the molecular viscosity ν, not a fluid property but depends strongly on the state of the turbulence and may vary considerably over the flow field. ν_t is proportional to a velocity scale $\hat{V}$ and a length scale L characterising the turbulent motion:

$$\nu_t \propto \hat{V} \, L \qquad (1)$$

Zero-Equation Models

For near-field problems the assumption of a constant eddy viscosity is not sufficient. Accordingly the distribution of ν_t over the flow field must be determined. The first model to describe this was suggested by Prandtl and is known as the Prandtl mixing length hypothesis. He assumed that the eddy viscosity ν_t is proportional to a mean representation of the fluctuating velocity $\hat{V}$ and a "mixing-length l_m".

The mixing-length model has been applied mainly for two-dimensional shear-layer flows with only one significant velocity gradient. The model is of little use in complex flows because of the great difficulties in specifying the distribution of the mixing length l_m. Further problems arise because the eddy viscosity and diffusivity vanish and so does the transport whenever the mean velocity gradient is zero, as must be the case e.g. in symmetrical flow.

One-Equation Models

In order to include the influence of the fluctuations on the surrounding flow, Prandtl and Kolmogorov suggested the use of the turbulent kinetic energy (TKE) as a dependent variable. Assuming $\sqrt{k}$ as the velocity scale, the relation for the eddy viscosity following equation 1 is:

$$v_t = C'\mu \sqrt{k}\, L$$

where $c'\mu$ is an empirical constant. This formula is known as the Kolmogorov-Prandtl expression. The length-scale, L, appearing in the above equation and also in the dissipation term of the k-equation, must be specified empirically. One-equation models account for advective and diffusive transport and also for memory on the turbulent velocity scale, and are therefore superior to the mixing-length hypothesis when these effects are important.

The application of one-equation models is restricted mainly to shear-layer situations since it is difficult to specify empirically the length-scale distribution in more complex flows. For calculating general flows, the trend has therefore been to move to two-equation models which determine the length scale from a transport equation.

Two-Equation Models

Within the class of two-equation models the Level-2½-model developed by Mellor and Yamada 1982 [74] and the k–ϵ-model (cf. Launder and Spalding 1972 [67]) became very popular. They use an additional vertically resolving evolution equation for the length-scale or a related quantity. The length-scale L characterising the size of those eddies which contribute most to the turbulent stresses is subject to transport and memory in a manner similar to the velocity scale $\sqrt{k}$. The length-scale determining equation need not have L itself as a dependent variable; any combination of the form $z = k^m L^n$ will suffice because k is known already from solving the k-equation. The combination $k^{3/2}/L$, which physically represents the dissipation rate ϵ, has by far achieved the greatest popularity for the practical reason that the ϵ-equation does not require a secondary source term near walls while equations for other variables do (e.g. Level-2½-model). The turbulence model which solves the k and ϵ-equations has become known as the k–ϵ-model.

In the standard k–ϵ-model the eddy viscosity concept is applied. It relates the fluxes of momentum and heat to the velocity and density gradients of the mean quantities. The Kolmogorov-Prandtl relation couples the mean flow equations to the state variables of the turbulence model. The basic advantage of the advanced model is the approximate but individual description of selected components of the Reynolds tensor. Exact transport equations for the tensor components can be derived from the Navier-Stokes and Reynolds equations (e.g. Hinze 1975 [47]). The empirical constant in the equation for the eddy viscosity in the standard model turns out to be a complicated implicit function in the advanced model. The content is a function of the turbulent shear number, the turbulent buoyancy number, and a wall correction (see Burchard & Baumert 1995 [14]).

Reynolds Stress Models

The models reviewed so far assume that the local state of turbulence can be characterised by one velocity scale and that the individual Reynolds stresses can be related to this scale. In Reynolds stress models the transport equations for the six Reynolds stresses and the three turbulent transports are solved directly (Rodi 1984 [88]). This approach does not remove the necessity of closing the model by experiments but has the advantage of relaxing the assumption of isotropy inherent in Boussinesq's viscosity assumption. Various simplifications of the additional transport equations exists in the so-called Algebraic Reynolds Stress closures, where the partial differential equations are reduced to algebraic relations for the individual stresses by either assuming local equilibrium of the Reynolds stresses or relating the transport stress to the transport of k and ϵ (Petersen 1992 [82]).

2. Short-period Wave Motion (Wind-Generated Waves, Periods of 5 to 20 s)

For the purposes of the PROMISE project, wave motion is especially important both as a source and sink of turbulent energy and by its influence on the mean flow.

A general overview of the principles of fluid flow and surface waves is given in van Rijn 1990 [110]. The Dynamics and modelling of ocean waves is discussed in Komen et al. 1994 [65]. Further major literature contributions are described below.

2.1 Field and Laboratory Investigations

A great contribution in this research area has been made by the MAST project G6/G8 Coastal Morphodynamics (see de Vriend 1993 and 1995 [22, 23]) by extensive field measurements and laboratory experiments.

Flume experiments (Liberatore and Petti 1992 [70]) were performed to investigate the energy transfer to higher frequencies, which has been observed in wave spectra behind a bar.

Laboratory experiments on wave height decay and surf beats on mild slopes were performed at the University of Florence and at Bristol University (Watson et al. 1994 [117]). Another series of 3-D wave experiments (Hamm 1992 [43]) was made with short-crested random waves on a plane beach with a rip channel.

Conley and Inman 1992 [16] analysed numerous synchronised time series from video cameras, pressure sensors, current meters, and hot film anemometers on natural beaches. They found a pronounced asymmetry in instantaneous sand transport and boundary layer phenomena between the wave crest and trough. The authors suggest the wave induced boundary ventilation is responsible for this asymmetry (see also Conley and Inman 1994 [17]).

2.2 Wave Models

Mathematical models of wave fields generally take a spectral approach (describing spectral moments), an intra-wave time-domain approach (describing the variation of the free surface elevation within the wave period), or a probabilistic approach (decomposing the wave field into generally non-linear components with a certain probability of occurrence).

Time-Domain Modelling

Research foci within the MAST project were the accurate modelling of linear dispersion and linear shoaling outside the surf zone (Dingemans 1994 and 1995 [28, 29]), non-linear shoaling, inclusion of wave breaking via a roller model (Sorensen et al. 1994 [92]), modelling of surf beats, and wave kinematics and integral properties of shoaling waves near the point of breaking (Madsen et al. 1994 [71]). A non-linear shallow-water model was used to describe the water motion in the swash zone in the case of irregular, groupy incoming waves (Watson et al.1994 [117]).

Frequency-Domain Modelling, Spectral Considerations

A crucial point in morphodynamical models is breaking. It is necessary (e.g. for the representation of bar formation) to take account of the transition zone between the point where the wave starts breaking and the point where they start dissipating energy (see Nairn et al. 1990 [77], Southgate & Nairn 1992 [94]). A theoretical model describing the flow in a breaking wave was developed by Jenkins 1994 [56].

Long-Period Motions

Long-period motions can be subdivided into low frequency waves (e.g. edge waves, surf beat) and vortical motion (e.g. shear instability of the long-shore current).

Attention in the G6/G8 project has been focused on the effects of modulated short waves. One of these effects is surf beat, a long wave phenomenon due to the variation in set-up between the higher and the lower waves in the groups. Roelvink 1991 and 1992 [89, 90] has developed a non-linear model of these long waves and shows the relevance for beach profile morphology.

2.3 Coastal Currents

In coastal morphodynamics waves and currents, not necessarily wave-driven, play an important role. In the following sections some results of the work on wave-current interaction and coastal current modelling in the G6/G8 project are indicated. For more information, see Soulsby et al. 1993 [93].

Furthermore numerical models for the simulation of wind- and wave-induced currents have been developed by Jenkins 1987 and 1989 [57, 58, 52, 53]. The effect of waves on the surface stress is investigated in Jenkins 1992 and 1993 [54] and [55].

More and more satellite observations are applied to investigate processes in the upper ocean and atmospheric boundary layer. Johannessen et al. 1996 [60] report of a cruise in Norwegian coastal waters where satellite observations with Synthetic Aperture Radar (SAR) are compared with simultaneous in situ measurements of currents, meteorology, etc. (see also Johannessen et al. 1996 [59]).

Wave Kinematics Without Currents

The wave orbital motion is one of the most important elements in sediment transport. Its asymmetry in shallow waters gives rise to a net transport even if there is no ambient current. An accurate description of this motion and the associated bed shear stresses is therefore vital to morphological models. Especially in the surf-zone, much of the observed behaviour of these quantities (Deigaard et al. 1991 [26]) is still poorly understood. Calculations of the orbital velocity on the basis of the cnoidal wave theory (Swart and Crowley 1988 [97]) show a significantly better prediction than with the linear wave theory.

Wave Kinematics With Shear Currents

If the waves propagate over a current field, the vertical variation of the current profile can have a strong effect on the wave orbital motion. This phenomenon was investigated within the G6/G8 project in further depth on the basis of previous work by Thomas 1990 [104].

Klopman 1993 [64] describes the interaction of shallow water waves on turbulent flow using a multiple-scales perturbation method to solve the Reynolds equations with a k–ϵ turbulent closure model.

Wave-Driven Currents

Only recently have there been attempts to formulate a consistent 3D model concept, to be incorporated in so-called "quasi-3D" or "2½-D" models (De Vriend and Stive 1987 [21]; Arcilla et al. 1992 [3]) or in 3D-hydrostatic models (De Vriend and Kitou 1990 [20]; see also van Dongeren et al. 1994 [108]).

A range of intra-wave boundary layer models, with various turbulence closure models, was extended to predict shear stresses under irregular waves and verified against measured data (Ockenden and Soulsby 1994 [79]; Myrhaug 1995 [76]).

A depth-integrated, short wave-averaged near-shore circulation model is presented by van Dongeren et al. 1994 [108], which includes the effects of the 3D current structure over depth. Lateral mixing plays an important role in the distribution of near-shore currents. Svendsen and Putrevu [96] show that the non-linear interaction terms between cross- and long-shore currents represent a dispersive mechanism that has an effect similar to the required mixing.

Residual Currents at the Shore face

Long-term evolution of coastal morphology requires a special view on coastal currents. Since most of the predominant current phenomena vanish after averaging over a sufficiently long period, seemingly unimportant phenomena, such as wave-induced boundary-layer streaming, Ekman-veering of the tidal currents and residual currents due to horizontal density gradients, turn out to contribute significantly to the long-term residual transport (Zitman 1992 [120]; Klopman 1993 [64]).

3. Bottom Boundary Layer

Two distinct bottom boundary-layer regions develop under a combined flow of waves and currents. In the immediate vicinity of the bottom, an oscillatory boundary layer exists of the order of 3–5cm in mild waves and 10–20cm in strong waves. The wave boundary layer is embedded in a larger planetary boundary layer. Thus, close to the boundary the shear stress and turbulent kinetic energy are due to both waves and currents, whereas above the wave boundary layer these quantities are associated only with the low-frequency flow (Grant & Madsen 1986 [42]).

3.1 Models

Many models have been suggested to describe the combined wave-current boundary layer, or only the associated bottom shear stress (see Soulsby et al. 1993 [93]).

In the past the bottom boundary layer has been modelled as an Ekman layer with eddy viscosity coefficients chosen to agree with some physical property like e.g., boundary layer thickness. Richards 1982 [87], on the other hand, has presented an alternative model based on a second-order closure scheme. This type of model yields both eddy diffusivity and boundary-layer thickness. Rahm and Svensson 1989 [85] derived a dispersion model for the bottom boundary layer, the presented model is restricted to describe the spreading of marked fluid elements in a horizontally homogeneous bottom boundary layer.

The upward dispersion of heavy particles in suspension in turbulent flows was studied by Noh and Fernando 1991 [78] using a numerical model. Brørs and Eidsvik 1994 [13] present a standard dynamic Reynolds stress model with conventional coefficients, applied to oscillatory boundary layer flows.

On a slope, an oscillatory flow with sediment entrainment is predicted to force a systematic turbidity current. For such a situation, the Reynolds stress model is expected to be significantly more realistic than few-equation models.

A model to predict the roughness in unsteady oscillatory flows over movable, non-cohesive beds is presented by Grant and Madsen 1982 [41].

4. Sediment Transport

One of the objectives of the PROMISE project is to apply dynamical output from pre-operational modelling to simulate sediment transport. Some recent developments in this context are reviewed below.

Suspended matter and sediment transport in the North Sea including coastal areas is discussed in different papers, e.g. van Alphen 1990 [107], Dronkers et al. 1990 [31], Dyer and Moffat 1994 [32], Eisma 1981 [33], Eisma and Irion 1988 [34], Dupont 1993 [36], McCave 1987 [73], and within the MAST project *Fluxes into the North Sea* [38]. Special focus on pollutants has been made by Eisma and Kalf 1987 [35], Sündermann 1994 [95], Zwolsman 1994 [121], Talbot 1981 [98], and in a technical report [86].

The classification of SPM by optical means as well as measurements (in-situ and in laboratory) and remote sensing is discussed in e.g. Althuis 1994 [2], Bale et al. 1994 [6], Bale and Morris 1987 [5], Kirk 1984 and 1991 [62, 63], Dekker 1993 [27], Dirks 1990 [30], Campbell and Spinrad 1987 [15], Krijgsman 1994 [66], Marees and Wernand 1992 [72], Roozekrans and Prangsma 1992 [91], Prieur and Satheyndrath 1981 [83].

4.1 Non-Cohesive Sediments

Non-cohesive coastal sediment transport modelling is a very difficult enterprise, in which we have to accept discrepancies between prediction and reality in the order of 100 % and more. The response of the transport to its hydrodynamic forcing is highly non-linear, it occurs in a variety of modes (bed load, suspended load, sheet flow) and it has a strong small-scale interaction with the bed (e.g. via ripple formation) (see de Vriend 1993 [22]).

Suspended load is usually modelled by a diffusion equation for the sediment concentration, either at the intra-wave scale or in a wave-averaged formulation. In the latter case, wave effects are introduced via the eddy diffusivity and bottom boundary condition. Moreover, in order to account for the wave drift, advective terms have to be included in intra-wave models and the drift has to be taken explicitly into account in wave-averaged models (see Fredsoe and Deigaard 1992 [39]).

Suspended sediment in the surf-zone is a special case, since most of the turbulence there is generated by the breaking waves. Deigaard et al. 1986 [25] developed an intra-wave hydrodynamic and sediment transport model which is able to predict the increase in suspended sediment concentration due to breaking waves.

Pedersen et al. 1992 [81] modelled the effects of plunging breakers on intra-wave suspended sediment motion.

Various issues on wave-averaged suspended load modelling for combined waves and currents have been addressed (see de Vriend 1993 [22]), such as

- the "wave-borne" sediment flux, which contributes significantly to the total transport (Davies 1992 [19]; Murray et al. 1992 [75]);
- flume experiments on entrainment and transport of fine sediment (Villaret and Latteux 1992 [112]);

- field measurements, in an estuary and in the surf-zone, of suspended load transport under waves and currents (Whitehouse 1992 [118]: Van Rijn and Kroon 1992 [111]);
- quasi 3D wave-averaged modelling of water and sediment motion (Katopodi et al. 1992 [61]);

In the G6/G8 project (de Vriend 1995 [23]), the vertical distribution of sand has been modelled by applying the diffusion concept together with a variety of turbulence models, some including the effect of turbulence damping and density stratification (e.g. Villaret and Latteux 1994 [113]).

Apart from some empirical formulae, the prediction of the occurrence and the properties of bed forms as a function of the hydrodynamic conditions and the sediment properties is still poorly developed. In G6-M sophisticated flow models were under development (Broker Hedegaard et al. 1992 [46]; Block and Davies 1992 [9]; Pedersen et al. [81]).

Further investigations have been done within the G6/G8 project (de Vriend 1995 [23]). Studies on the influence of bed ripples on sediment transport have been performed. Various concepts were used to model the water and sediment motion around bed ripples, either based on discrete-vortex simulation (Hansen et al. 1994 [44]; Block et al. 1995 [10]) or on a turbulent diffusion model (mainly $k-\epsilon$, e.g. Tran Thu and Temperville 1994 [106]).

On a larger scale, the modelling of the long-shore sediment transport in a real-life environment was studied, taking into account the presence of shear waves (Deigaard et al. 1994 [24]).

A model to predict the roughness in unsteady oscillatory flows over movable, non-cohesive beds is presented by Grant and Madsen 1982 [41].

A simple morphological model is presented by Hulscher et al. 1993 [48] describing the interaction between tidal flow and an erodible bed in a shallow sea.

Measurements

Huntley et al. 1994 [49] measured sea bed drag coefficients in the southern North Sea using pressure sensors and moored current meters.

Hay and Sheng 1992 [45] have investigated vertical profiles of suspended sand concentration and size by means of multi-frequency acoustic profiling data collected in 1989 during a near-shore experiment. The data were acquired with acoustic sounders.

4.2 Cohesive Sediments

In contrast with sand cohesive sediment behaviour depends on a much larger number of parameters, which are hardly known.

G6-M (de Vriend 1993 [22]) has spent a good deal of effort on the development of standards for the characterisation of cohesive sediments from the point of view of transport and erosion/deposition behaviour. This has led to a list of 28 characteristic parameters as a starting point for standardisation (Berlamont et al. 1993 [7]).

Besides, an inventory was made of the techniques which are used in the various laboratories involved in G6-M to measure these parameters.

For the calibration of sediment models with realistic data (data assimilation), only a few (bulk) parameters can be tuned. This follows from the large error margins that are found in the suspended sediment data (high natural variability), and the difficulties of modelling bed consolidation (the properties of the bottom are poorly known).

The difficulties that must be solved in the application of 2D and 3D sediment models based on the concepts of Partheniades and [80, 8] with one sediment fraction are already significant. Therefore the calibration of a space-varying settling velocity, and a space-varying erosion rate for one suspended sediment fraction in large-scale models, using in-situ data and remote sensing data, might be the first aim and are discussed with special emphasis on the North Sea in the following papers: Boon 1995 [11], Boon and Baart 1996 [12], Vos and Schuttelaar 1995 [116] and Vos et al. 1997 [115].

Another step on the way to cohesive sediment modelling is the understanding and the quantitative modelling of the various transport processes (cf. Puls et al. 1994 [84], Visser 1993 [114], Teisson 1991 [99]; Teisson et al. 1993 [101].

One of the key processes in the water column is flocculation. As the flocs can be very fragile, direct non-disturbing in-situ measurements were made with various underwater video cameras (Van Leussen and Cornelisse 1993 [109]; Fennessy et al. 1994 [37]) to observe their behaviour. Flocs occupy large volumes at a relatively low mass concentration. Hence hindered settling effects give rise to the formation of lutoclines in the vertical distribution of the sediment concentration and thus influences the turbulence structure of the water motion. This phenomenon was studied with algebraic eddy-viscosity models (Costa 1994 [18]), k–ϵ and Reynolds stress turbulence models (Galland et. al. 1994 [40]; Le Hir 1994 [68]) and with high-resolution two-phase flow models (Teisson and Simonin 1993 [102]; Le Hir 1994 [68]).

Exchange processes between the bed and the water column govern, to a large extent, the horizontal transport in coastal waters. Erosion processes are especially important, but not yet fully understood.

Very soft mud layers (fluid mud) are not eroded particle by particle, or floc by floc, but rather via massive entrainment. Experiments in an annular flume were simulated with a turbulent kinetic energy model (Winterwerp and Kranenburg 1994 [119]). These soft mud layers are also very effective in damping surface waves, a process which appears to be described reasonably well by models which treat the mud as a viscous fluid (de Vriend 1995 [32]).

Deposition

Various researchers have formulated deposition models, mostly on the basis of laboratory tests (de Vriend 1993 [22]).

Consolidation

The incorporation of consolidation in long-term cohesive sediment transport models can have a dramatic effect on the fate of the sediment and the attached pollutants.

Alexis et al. 1992 [1] give a review of consolidation theories, and elaborate and substantiate these on the basis of laboratory data from the literature. So far, the consolidation algorithms (if any) in cohesive transport models are purely empirical. Several models have been tested (e.g. Alexis et al. 1992 [1], Teisson et al. 1992 [100]; Le Hir and Karlikow 1992 [69]).

Within G8-M a large number of experiments were carried out, also with sand-mud mixtures (Huysentruyt 1994 [50]) and with gradual sediment input. Model verifications were rather successful, but revealed that the constitutive equation which relates the effective stresses to the pore ratio remains a weak point in consolidation modelling (de Vriend 1995 [23]). New formulations have therefore been tested (e.g. Toormann and Huysentruyt 1994 [105]).

Erosion

The erodibility of cohesive sediment beds is usually tested in annular or recirculating flumes with steady flow (also see Berlamont et al. 1993 [7]). The number of unknown parameters in the accepted erosion formulae is so large, however, that the formulae can always be tuned to the measured data. Besides, the results are very sensitive to the bed shear stress, a parameter which is hard to determine in real-life cases. Therefore, the predictive ability of the present erosion formulae is limited and further research is needed (de Vriend 1993 [22]).

Resuspension

Resuspension processes and seston dynamics have been considered by Jago et al. 1994 [51] and experiments in the southern North Sea have been performed.

Wave Effects

Surface waves over a mud bed can cause fluidisation (via pore pressure) and liquefaction (via shear stresses). Either of these effects disrupts the bed structure and brings the sediment into suspension and make it available to transport e.g. by weak currents or gravitation (de Vriend 1993 [22]).

Turbulent Aspects

Two 3-D models were used to simulate turbulence in heavily-laden flows, viz. a Reynolds stress model and a two-phase flow model (Teisson et al. 1992 [103]). This has led to various new insights (de Vriend 1993 [22]), such as:

- The damping of turbulence has a major effect on the shear stresses in the fluid and the concentration profile of the sediment.

- There are large differences between eddy viscosity and eddy diffusivity, the former being much less sensitive to damping than the latter; this questions the Reynolds analogy.

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