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Sediment Fluxes in Shelf Seas Modelling and Monitoring

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This is a review paper, assessing progress reported in a Special Issue (Prandle and Lane, 2000) of *Coastal Engineering* focusing on simulation of SPM in the North Sea, against issues over a diverse range of shelf seas and their coastal margins. The broad objectives of reproducing the characteristics of sediment fluxes off an open coast and relating these to tidal and wave forcing were achieved. However, accurate computation of these fluxes remains sensitive to largely empirical coefficients used in determining erosion and deposition rates. Bed roughness strongly influences both these coefficients and the associated near-bed current magnitudes (including wave impact thereon). Bed roughness can change significantly over a tidal cycle and dramatically over seasons or in the course of a major event. Accurate simulation of sediment fluxes on a day-to-day basis is constrained by dependency on the initial distribution of mobile sediments. The latter depends on rates and locations of original sources and the time history of preceding events. Remote sensing via aircraft could provide data for assimilation into such models to circumvent these constraints. The approaches described here can be readily applied to other coastal regions to indicate the likely distributions and pathways of known sediment sources. However quantitative simulations will require an associated observational programme. A subsequent stage is to understand the evolving balance between the forecasted sediment movement – the resulting morphological adjustments and thence modifications to the prevailing tidal current and wave regimes.

Key words: Suspended sediments, Modelling, Monitoring, Tides, Waves, Morphology, North Sea

INTRODUCTION

Interest in simulating SPM (suspended particulate matter) ranges from: (i) concentrations which determine light occlusion impacting on primary production, (ii) fluxes which provide pathways for adsorbed contaminants and (iii) net accretion/erosion which determines bathymetric evolution. Erosion and transport are generally determined by tidal and storm currents, enhanced in shallow water by wave stirring. However modelling of these processes is complicated by the immediate localised feedback between the composition (fine to coarse) and form (ripples, waves) of the bed which determines bottom-roughness, hence bottom friction and turbulence structure and thereby propagation of tides and waves and the interaction between these (Fig. 1). Moreover, on larger and longer space and time scales, the exposure to tides and waves adjusts to the inter-related evolving bathymetry. On even longer scales, the influence of changes in both mean sea level and sources of sediment can change the nature of this former inter-relationship.

This review provides a brief background to the inter-relationships between theory, observations (Fig. 2) and modelling of SPM erosion, transport and deposition. Illustrations of these inter-relationships are

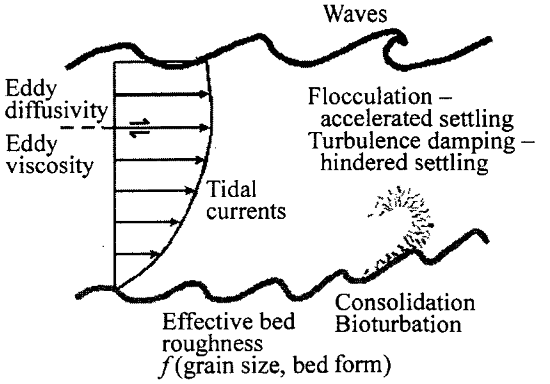

Fig. 1. Small scale processes in sediment erosion, transport and deposition.

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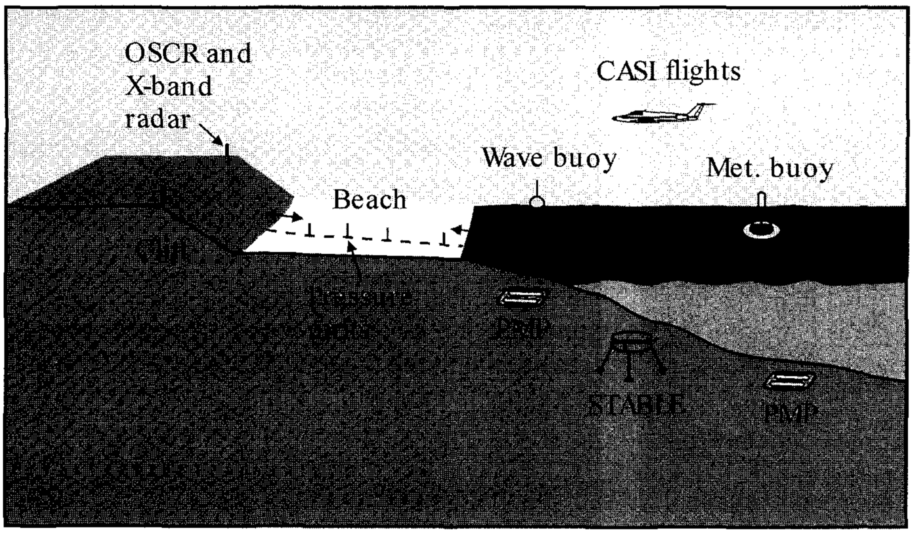


Fig. 2. Instrumentation deployed in coastal sediment experiment (OSCR, Ocean Surface Current Radar; CASI, Compact Airborne Spectral Imager; PMP, Proudman Oceanographic Laboratory Monitoring Platform; STABLE, Sediment Transport And Boundary Layer Equipment).

then provided on four time – space scales, namely: (i) near bed processes, (ii) vertical profiles at a single-point, (iii) coastal simulations and (iv) longer term bathymetric evolution. A subsequent summary is followed by some suggestions for ways forward.

Sediment transport in the marine environment at first appears deceptively simple. It often subsequently manifests itself as impossibly complex – frustrated by the deficiencies in observational technology. However it is important, there are tractable elements and technology developments should continue to provide encouragement for persistent researchers.

INTEGRATING THEORY OBSERVATIONS MODELLING

Theory

Prandle (1997a) showed that the amplitudes of the various tidal constituents in SPM time series are proportional to

$$C_\omega = \frac{\gamma k \rho [U^n]^\omega}{D(\omega^2 + \alpha^2)^{1/2}} \tag{1}$$

assuming a rate of sediment erosion,

$$ER = \gamma \rho k U^n \tag{2}$$

where $[U^n]^\omega$ represents the amplitude of the tidal constituent ω in the expansion of the tidal current raised to the power n, k is bottom friction coefficient and γ is an erosion rate coefficient. The parameter α is the 'half-life' between erosion and deposition for the assumption of exponential settlement used by Prandle.

These half-lives are determined by the advective deposition time D/w_s (D water depth, w_s fall velocity) for coarse sediments with w_s of O(0.01 m s^{-1}) and by dispersive deposition K_{zz}/D^2 (K_{zz} vertical diffusion coefficient) for finer sediments with $w_s < 0.001$ m s^{-1}. Fig. 3 shows typical half-lives which range from O(1 m) for coarse sediment in shallow water to greater than 1 day for fine sediments in deeper water. Fig. 4 illustrates the concentrations corresponding to Eq. (1) for this range of sediments subjected to forcing at frequencies, ω, ranging from waves of a few seconds to the spring-neap tidal cycle. This diagram can be used to interpret the SPM time series shown in subsequent sections.

Similarly Fig. 5 shows maximum (time and depth averaged) SPM concentrations for unlimited supply. These values are consistent with concentrations found in estuaries but far exceed concentrations in shelf seas. This emphasises the 'supply-limited' nature of SPM distributions in most shelf seas.

Observations

Observations are crucial to developing and assessing SPM models. In situ concentrations are routinely monitored acoustically (ABS, Acoustic backscatter probes providing vertical profiles, single-point multifrequency probes provides information on grain size), optically (OBS, optical backscatter and transmissometers) mechanically (via pumped samples, bottles and traps). More recent developments of in-situ laser particle sizers provide invaluable information on particle spectra that can be corrupted in mechanical samplers.

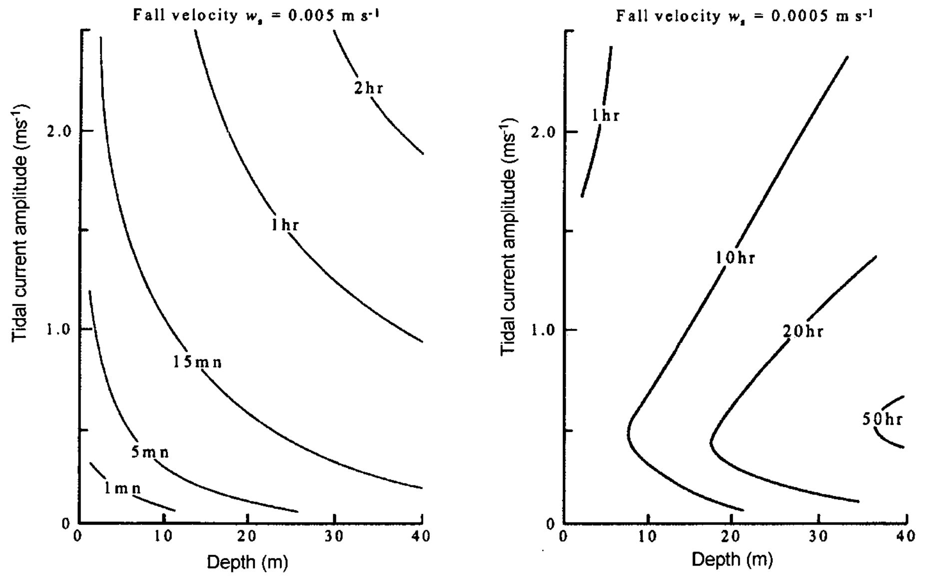


Fig. 3. Half lives of sediment in suspension.

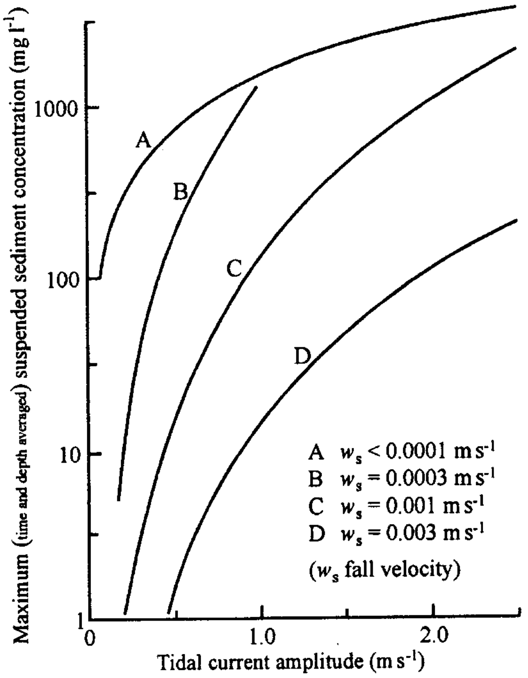


Fig. 4. Maximum (depth and tidally averaged) sediment concentrations.

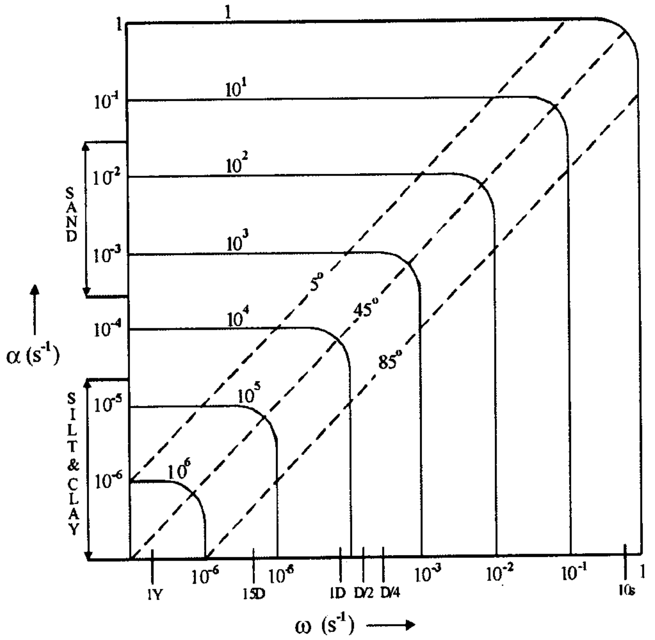


Fig. 5. Relative magnitudes of SPM spectra associated with tide and wave actions. Dotted lines show phase delay of SPM concentration relative to peak velocity, α=1/half life of SPM in suspension, ω=frequency of erosional agent.

Likewise AVHRR and optical sensors on satellites and aircraft (SeaWiFs, CASI) provide indications of surface concentrations. The use of multiple wavelength sampling provides a basis for distinguishing chlorophyll, fine and coarse sediments but variations in atmospheric correction parameters and in the nature (especially organic) of the SPM limit the quantitative value of such remote sensing. Exploitation of such imagery includes the development of neural networks simulating the observed image and utilising the patterns of plumes, fronts, etc.

Fig. 2 illustrates a range of instrumentation used, indicating the varying nature of the associated coverage. Thus while remote sensing from satellite and aircraft provide occasional surface snapshots of SPM concentrations, (subject to complex calibration, geographical and atmospheric correction), most in situ instruments provide continuous long-term time series but at a single point. By contrast, although radar only measures surface signals it does provide continuous time series over a wide area. Moreover, for waves, the general validity of linear theory allows such surface signatures to be extrapolated into depth profiles allowing, for the X-band radar, an indirect estimation of bathymetry.

Models

SPM concentration models involve the solution of the ‘conservation of mass’ equation:

$$\frac{dC}{dT}+U\frac{dC}{dX}+V\frac{dC}{dY}+W\frac{dC}{dZ} = K_x\frac{d^2C}{dX^2}+K_y\frac{d^2C}{dY^2}+K_z\frac{d^2C}{dZ^2}+\text{SOURCES}+\text{SINKS} \quad (3)$$

(Rivers, Adjacent Seas Atmosphere, Benthic)

The horizontal advective velocities U and V are generally specified from tidal models.

Application 1 discusses formulations for sinks and sources.

Application 2 discusses the solution of the vertical components, i.e. single-point solution.

Application 3 extends to larger-area simulations in which these vertical exchange processes are integrated with tidal models to satisfy 3D mass conservation.

Application 4 notes the limits to longer-term integrations based on ‘bottom-up’ solutions to (3).

Given models and observations, data assimilation (being the interface between them) is an essential component in simulation systems. Assimilation is used to transfer observed information to update the model state, the model forcing and/or model coefficients. The challenge is to take advantage of the complementary character of models and observations: the generic, dynamically continuous character of process knowledge embedded in models vs. the specific, quantitative character of observed data. Specification of the sources and sinks in SPM (suspended particulate matter) simulations is severely complicated; in particular, availability of sea bed sources depends on the chronology of previous deposition and associated consolidation rates. Satellite images of (surface) SPM concentrations can be used in conjunction with model simulations to infer the magnitude of discrete sediment sources. Aircraft surveillance using multi-wavelength imagery promises to differentiate between the reflectance associated with chlorophyll and various sediment fractions and allow model verifications. However, the need for atmospheric corrections is likely to involve continued reliance on in situ calibrations.

APPLICATION 1: NEAR-BED PROCESSES

Figs. 6 and 7 provide examples of recent developments (Thorne and Hardcastle, 1997) in measuring near-bed SPM, turbulence and bed feature migration.

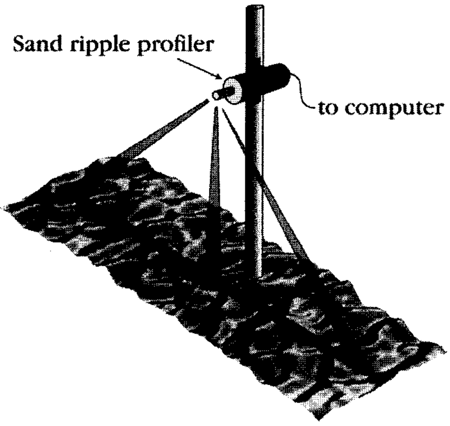


Fig. 6. Technology development for measuring near-bed sediment movement.

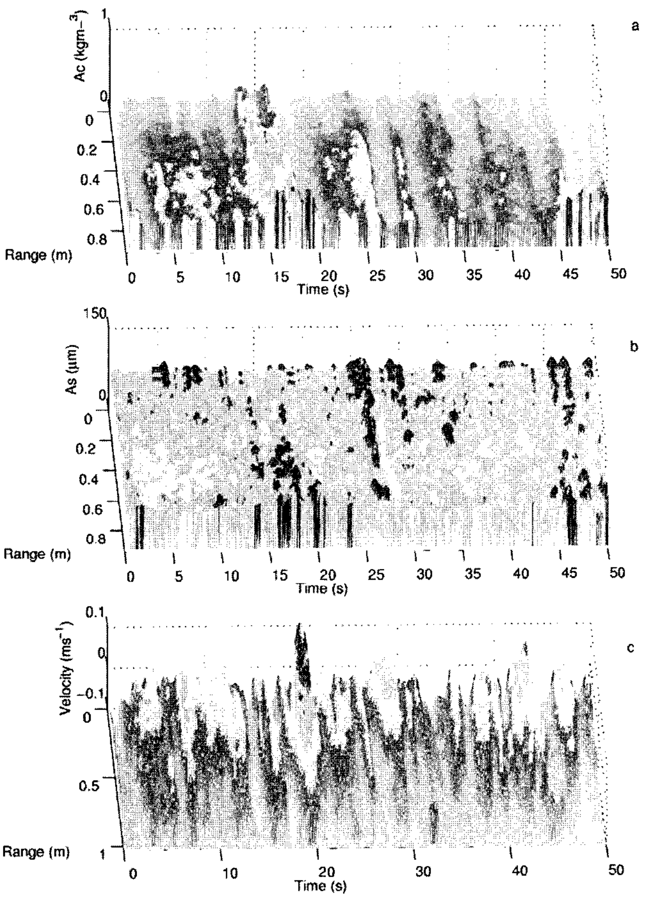
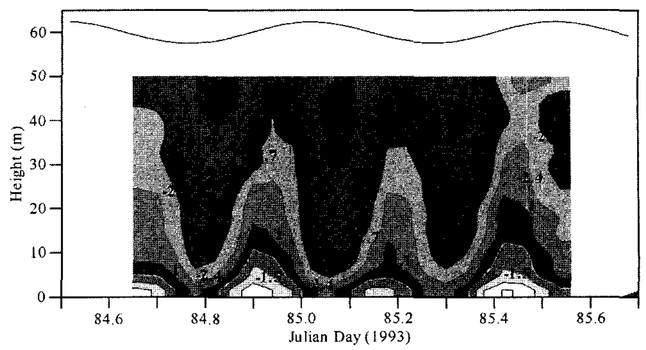
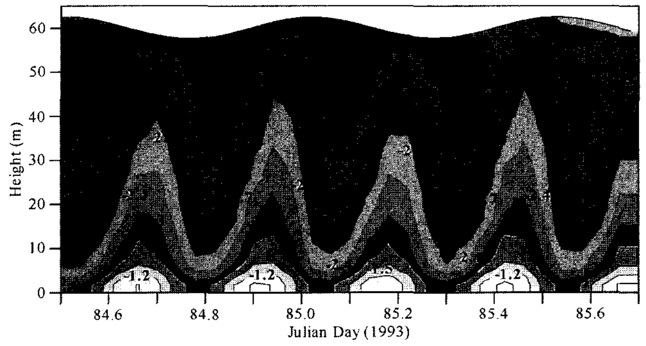


Fig. 7. Observations of near-bed sediment movement off Holderness(Proudman Oceanographic Lab., Annual report 1995-1996) (a) concentration, (b) particle size, (c) velocity. Range denotes distance vertically below sensor.



22 hour measurement of turbulent dissipation rate



Model simulation of turbulent dissipation rate

Fig. 8. Observed and computed vertical profiles of turbulence over a tidal cycle. Dissipation contours in $\log_{10}W\ m^{-3}$ (Simpson *et al.*, 1996).

Such process studies are progressively unravelling the component mechanisms that are integrated into the bulk-formulae used to parameterise erosion, transport and deposition of SPM.

Classically erosion of seabed material is assumed to occur when the bed shear forces exceed the resistance of the bed sediment. The resistance of the bed is characterised by a certain critical erosive shear stress. This critical stress is determined by several factors, such as, the chemical composition of the bed material, particle size distribution and bioturbation. Since often only qualitative information on the type of bed is available, usually a uniform value for this critical shear stress is employed in large-scale models. Erosion of sediment is induced by the bed stress due to tidal and wind-induced advective flows and surface waves.

Erosion is often assumed proportional to the excess of the applied shear stress over the critical bed shear stress for erosion (Parthenaides, 1962). The wide ranges found, sometimes factors of 10 or more, show the difficulty in formulating robust portable models.

Whether or not a particle will settle to the bed depends upon its size, density and the chemical conditions of the surrounding water system. Sedimentation is the process describing the settling of particles within the water column. The rate of downward mass transport (sedimentation) is equal to the product of the near-bed settling velocity, the near-bed concentration and threshold factor. A characteristic feature of cohesive sediments is the ability to form aggregates (flocs) that settle to the bed (Krone, 1962).

APPLICATION 2: VERTICAL PROFILES AT A SINGLE POINT

The combined effects of tides and waves induce stresses at the sea bed which simultaneously generate turbulent eddies and sediment erosion. The subsequent pathway of any eroded particle depends on a balance between its settling rate (excess density) and its movement via current components associated with tides, waves and turbulence. Baumert *et al.* (2000) describe the fundamental equations governing the generation and decay of turbulence associated with wave and tidal forcing. Numerical techniques for practical solution of these equations are also described and applications illustrated. These generic models are well validated against microstructure measurements from free-falling sensors; however, some difficulties remain in the reproduction of the background levels which determine layer exchange rates in stratified conditions.

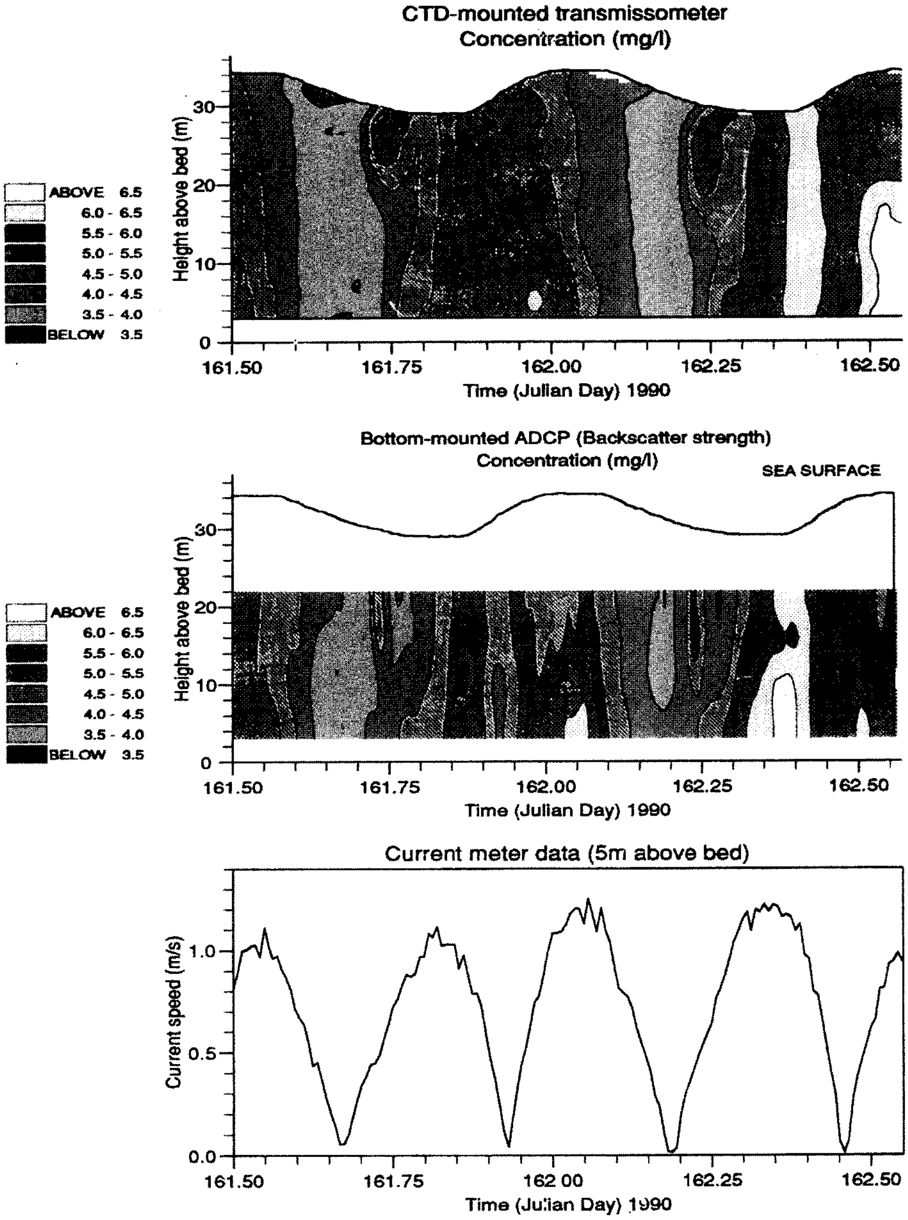
In deep water, the spectral gap between tides and waves enables their simulations to be entirely independent. In shallower water, their non-linear interactions become of first-order importance.

Fig. 8 shows an example of vertical profiles of turbulence intensity observed and modelled at a single point.

Fig. 9 indicates similar observations of SPM concentrations over a tidal cycle.

APPLICATION 3: COASTAL SIMULATIONS

A comprehensive observational experiment aimed at quantifying sediment movement was undertaken from '92 to '95 along a 30 km section of the UKs east coast. Currents, waves and concentrations of suspended particular matter (SPM) were monitored by an array of in situ, radar and remote sensing, instrumentation shown schematically in Fig. 2. Currents, wave parameters, pressure, temperature and conduc-



CTD-mounted transmissometer Concentration (mg/l)

Bottom-mounted ADCP (Backscatter strength) Concentration (mg/l)

Current meter data (5m above bed)

Fig. 9. Observed vertical profiles of SPM concentrations over a tidal cycle in Dover Strait (Prandle, 1997b).

tivity were recorded by the instruments shown. Transmissometers and both optical and acoustic backscatter probes were used to measure SPM concentrations.

Fig. 10 illustrates currents, waves and SPM concentrations observed and modelled in this study.

Fig. 11 shows a comparison of SPM time series measured by an OBS and a transmissometer. Each of these instruments has its own calibration peculiarities. Moreover all of these calibrations vary as the mean particle size changes. Optical devices rely on occlusion of light (transmissometer) or reflection (OBS) the signal is dependent on the surface area of the particle and hence the recorded signal needs to be multiplied by a representative particle radius *R* to indicate concentration, i.e. the apparent concentrations are more sensitive to finer scale particles. The plate-like character of some fines adds additional complication. Conversely acoustic backscatter (in the range of frequencies used in ABS instruments) increases with particle volume and hence this instrument is more sensitive to coarse particles. Thus the discrepancies indicated in Fig. 11 illustrate the sensitivity of the calibrations to variations in particle size spectra. Unfortunately these spectra change between sea bed and sea surface, over a tidal period, over the spring-neap tidal cycle, seasonally and during storm and wave events. The optical instruments also

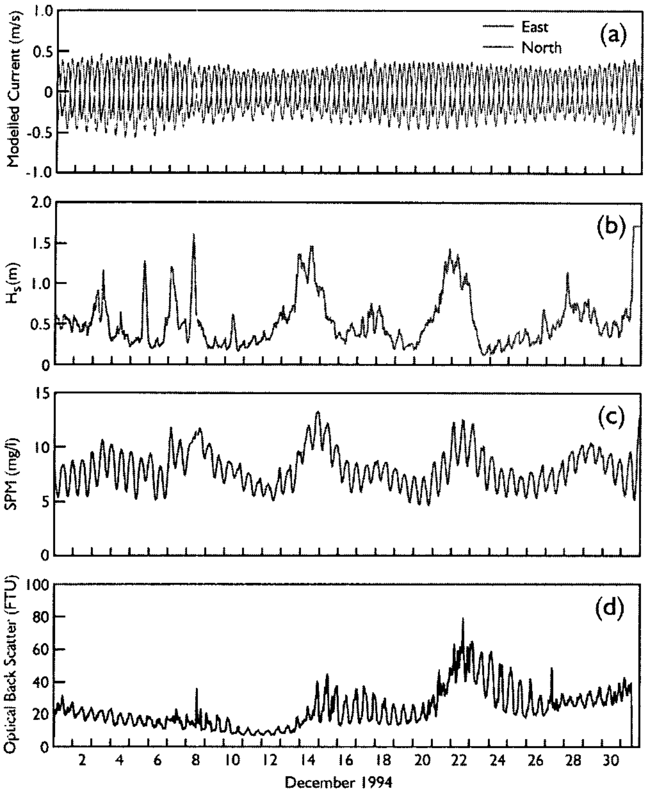


Fig. 10. Observed and computed currents, waves, SPM concentrations over 30 days (a) computed currents, (b) observed waves, (c) computed SPM and (d) observed turbidity (Prandle *et al.*, 2001).

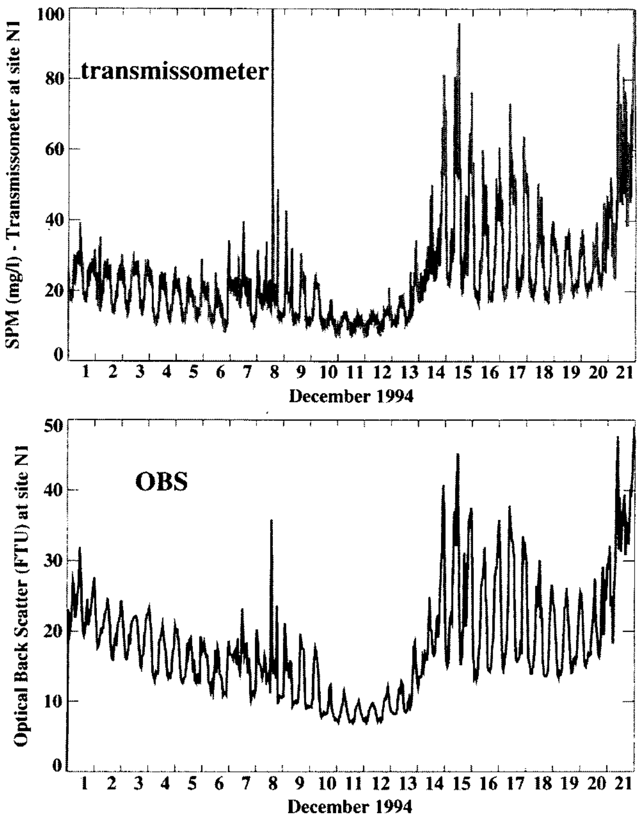


Fig. 11. Transmissometer vs OBS SPM concentrations over 30 days (Prandle *et al.*, 2001).

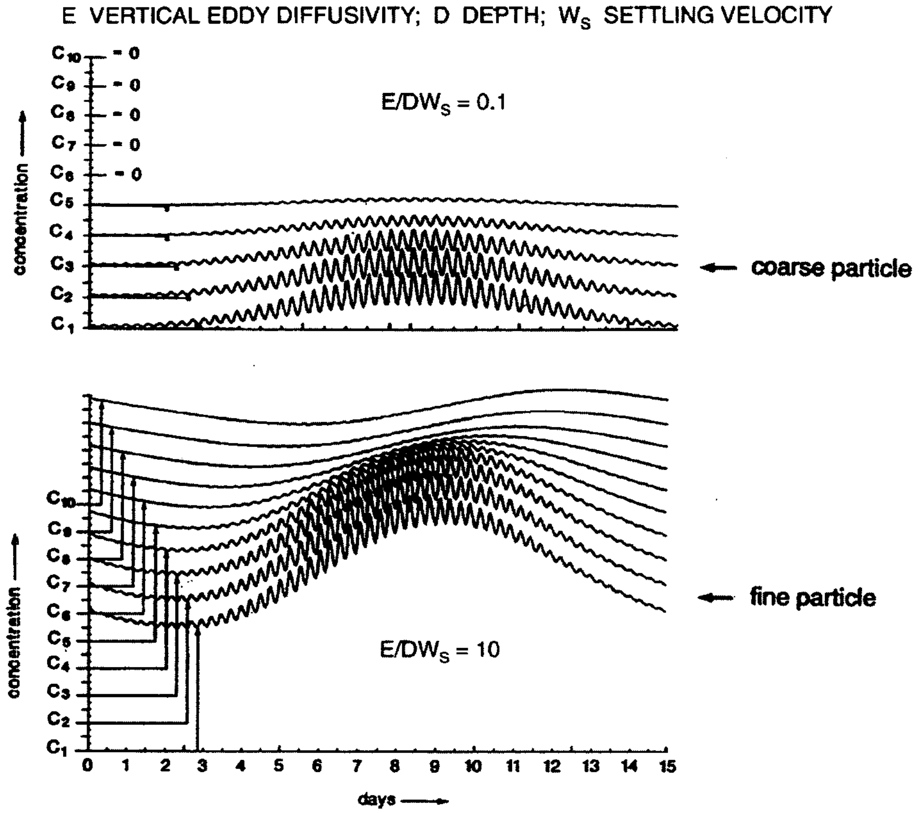


Fig. 12. Model simulations of SPM over a spring-neap tidal cycle. C1, C2, ... C10 indicate concentrations st fractional heights above the bed of $Z^{1/2}$=0.05, 0.15 to 0.95 (Prandle, 1997b).

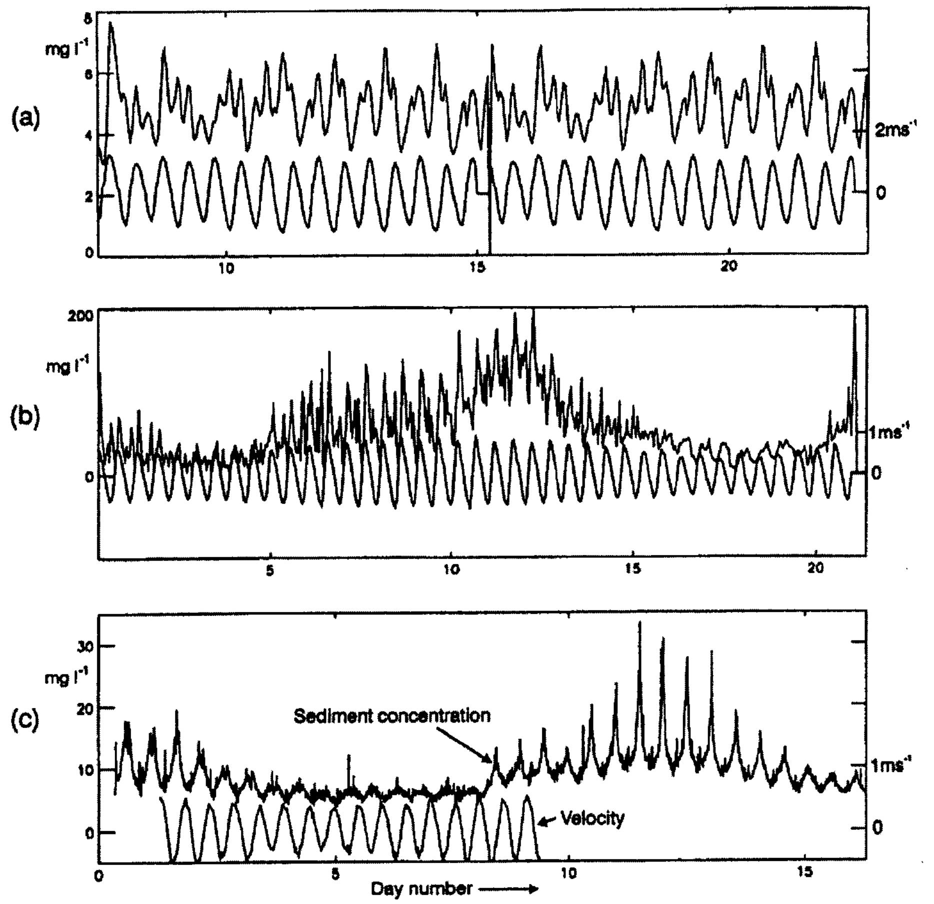


Fig. 13. Comparison of SPM time series from coastal, open sea and estuarine environments (a) Dover Strait, open sea, (b) Mersey estuary, (c) Hodemess coast (Prandle, 1997a).

experience fouling and all of the instruments can be swamped above certain concentrations.

Fig. 12 shows schematic model simulations indicating how, by appropriately varying the sediment types, such models can be used to reproduce these observations.

Fig. 13 provides a comparison of a range of tidally-dominated SPM concentration time series from a range of locations, namely: Holderness (the above coastal experiment), the Dover Strait and the Mersey estuary. The peculiar characteristics of the SPM time series as distinct from the closely related tidal current time series reflect the influence of sediment type and availability.

APLICATION 4: BATHYMETRIC EVOLUTION

In the longer term, difficulties arise in the specification of the available sources of sediments typically sea-bed, coastal, riverine and organic. While large area, long-term simulations can link these sources, specific sequences of events are often involved-with a resulting accumulation of errors in simulation. Net bathymetric evolution is even more difficult, since it involves the net temporal integration of the spatial divergence of all simulations. It is generally concluded that extrapolation using such primitive equation ('bottom-up') models is severely limited-effectively that they can only indicate pathways and likelihoods of erosion/accretion for periods of a few years. Further extrapolation often makes use of geomorphological (top-down) models which derive stability regimes based on geological evidence of coastal movements.

The fundamental uncertainties in modelling SPM fluxes arise from: (i) the dominant role of sediment sources, information on which is often incomplete or inaccurate (extent of source material and associated particle type spectra), (ii) relatively simple (bulk) erosion and deposition formulae (especially regarding the influence of flocculation), based on the observational information available, (iii) insufficient information on bed surface sediments (including seasonal variation) available for resuspension. There are further inaccuracies associated with descriptions of tidal, surge and wave dynamics but these are generally relatively well-prescribed. However, the sensitivity of calculated net long-term advective volume fluxes to model characteristics and set-up remains significant.

Available observations suffer from similar fundamental shortcomings, namely: (i) calibration from sensor units to concentration including sensitivity to particle size spectra in optical and acoustic instruments and to atmospheric corrections and sun angle effects in remote sensing; (ii) unresolved particle-size spectra; *(iii)* limited spatial and temporal coverage: remote sensing data provide high resolution spatially but for the surface and at low resolution in time.

On the longer time scale, information in sediment cores (choice of location crucial) may be dated using seasonal striations, specific contaminants (radio nuclides, Pb-210, etc.) and various natural chemical signals or biological fossils. The range of such techniques is expanding rapidly providing multiple opportunities to derive both geographic provenance and associated age. Both LIDAR (Light Detection and Ranging) and SAR (Synthetic Aperture Radar) have been used to determine sequences of bathymetric evolution.

A link between such bottom-up and top-down models can be made by using bottom-up models to formulate generic expressions for the controlling dynamics and testing these against morphological statistical derivations.

SUMMARY

Modelling of SPM fully utilises recent developments in fine resolution 3D hydrodynamics (tidal) and associated shallow-water wave propagation models. Likewise recent developments in coupling these together with various turbulence-closure models provide excellent, detailed descriptions of the fluid dynamics. Algorithms relating the associated bed stresses with rates of erosion are plentiful but the range and mixture of bed materials, the chemical and biological influences thereon, leave scope for empiricism. Likewise, settling rates can, in principle, be accurately simulated, however at higher (near bed) concentrations particles interact (flocculation and hindered settlement) and can modify the fluid dynamics.

Evaluation of generic turbulence models is restricted by the availability of direct measurements of turbulent intensity. Likewise, evaluation of associated SPM models is restricted by both the accuracy and spatial resolution of observations. The accuracy is restricted by the varying sensitivity of optical and acoustic sensors to the pertaining spectrum of particle diameters. The spatial resolution is limited to single points (or limited profiles) in OBS and ABS sensors and to surface values from satellite or aircraft sensors. Techniques to circumvent these shortcomings are described by Gerritsen *et al.* (2000) whereby the spatial patterns of surface imagery are used to validate models.

The more general strategy to overcome these difficulties in providing observational data sets to evaluate SPM models is illustrated by Prandle and Lane (2000). The Holderness Experiment employed duplication of sensors (transmissometers, OBS, ABS) and rigs (along parallel adjacent cross-shore profiles) and utilised ships, aircraft, satellite and radar alongside such in situ observations.

WAYS FORWARD

The severest constraints in modelling dynamics arise from inadequacies in accuracy and resolution of the bathymetry. For SPM simulations, lack of information on particle size distributions of suspended sediments is a major deficiency along with ignorance of the nature and distribution for surficial sediments. The use of aircraft surveillance to provide SPM distributions (sea surface) may, via assimilation techniques, circumvent the latter problem.

A subsequent stage is to understand the evolving morphological equilibrium between bathymetry and the prevailing tidal currents, and waves and mean sea level. In such equilibria, the requirement for near-zero net accretion and erosion provide demanding criteria for simulation models.

Analyses of the time-series recorded by OBS, ABS and transmissometers to provide information on size spectra, availability and rates of erosion and deposition provides both theoretical and technological challenges. Further development of depth profiling and side-sweeping acoustic instrumentation is similarly important. Studies of basic processes in near-full scale flumes will continuously enhance our understanding of the relationships between tide- and wave-induced stresses and associated sediment erosion.

Whereas the synoptic remote sensing image based concentrations adequately represent the large scale horizontal variability of SPM, in situ data can provide information on more detailed aspects of the (erosion/sedimentation) processes that determine the SPM transport and the variability over the vertical. New and improved sensors like SeaWiFS, MODIS and MERIS (satellite names) will allow the use of simpler and more accurate conversion algorithms.

At the moment, the winter period may be considered as a 'grey area' in our observations of the SPM transport. Dedicated measurement and monitoring campaigns to fill this winter gap is one of the challenges. The design of new, comprehensive networks exploiting synergistic aspects of a range of instruments/platforms integrally linked to modelling requirements/capabilities is a major challenge.

The scope of monitoring, modelling and theoretical developments described highlights the need for collaboration interdisciplinary and internationally. The value of test-bed data sets (e.g. UKs North Sea Project 87 88 and Holderness Coastal Experiment '92–'94) is evident. The requirement is for simultaneous, comprehensive, extended observational deployments with associated calibrations and sea-truth data. These data need to be quality assured, and stored systematically for accessible dissemination. The ultimate derivation of robust, portable SPM models depends on availability of a range of such test-bed data sets from a wide range of shelf seas i.e. parallel programmes across latitudes, scales and exposures.

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