OVERVIEW OF COAST3D PROJECT

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1. INTRODUCTION

A great deal of research has been devoted in recent years to modelling and measurements of waves, sediment transport and morphodynamic evolution on coastlines that are notionally straight and uniform, and these are now reasonably well understood. However, many of the coastlines that are of importance in practical applications do not conform to this ideal, but either have imposed non-uniformities such as headlands, river mouths, and manmade structures, or they depart spontaneously from two-dimensionality due to morphological non-uniformities such as rip-channels leading to dissected breaker bars.

These types of coastline have been addressed by the COAST3D project, a collaborative project co-funded by the European Commission's MAST-III Programme and national sources, running from October 1997 to March 2001. The project, which was undertaken by a consortium of 11 partners from five EU states (UK, Netherlands, France, Spain and Belgium), had the following objectives (see also Soulsby 1998):

- to improve understanding of the physics of coastal sand transport and morphodynamics
- to remedy the present lack of validation data of sand transport and morphology suitable for testing numerical models of coastal processes at two contrasting sites
- to test a representative sample of numerical models for predicting coastal sand transport and morphodynamics against this data
- to deliver validated modelling tools, and methodologies for their use, in a form suitable for coastal zone management

2. EXPERIMENTS

The first two objectives were achieved by making field measurements purpose-designed for numerical model evaluation, with adequate boundary conditions and a dense horizontal array of measurement points, in conditions typical of the European coastline. Previous coastal experiments in Europe and elsewhere have placed their main emphasis on hydrodynamics; an innovative feature of the present project is that the emphasis throughout is on sand transport and morphodynamics. Another distinctive feature is that the focus is on non-uniform (3D) coasts, rather than on the relatively well understood (but possibly unrealistic) uniform 2D case. Four field experiments have been successfully performed, resulting in large amounts of high quality data on water levels, currents, waves, sediment transport and bathymetric changes.

Egmond

The first two experiments took place at Egmond-aan-Zee on a quasi-2D sandy stretch of the Dutch coast (see map at front of Volume), with a pilot and main experiments in spring and autumn 1998 respectively (Ruessink, 1999). Although the coastline and bathymetric contours appear on charts to be nearly straight, on direct inspection it is seen that there is a natural three-dimensionality produced by rip-channels. These intersect a bar system and have a major effect on the hydrodynamics and sediment dynamics of the coast. The site is regarded as "2.5–dimensional" as a result of these sedimentary non-uniformities, and the departures from 2-dimensionality are an important aspect of this experiment. The dynamics of this west-facing sandy beach are dominated by storm waves from the North Sea. The meso-tidal range and currents, and storm surges, also play a significant role. Basic parameters at the site have been continuously monitored for a number of years, in conjunction with the Dutch national KUST*2000 project.

The measurements at Egmond were greatly aided by the use of the WESP – an approximately 15m high amphibious 3-wheel vehicle capable of operating on a beach and into water up to 6m deep. It can perform bathymetric surveys, deploy and recover instrumented tripods, and tow a 3.5m square and 2.5m high instrumented trailer (the CRIS). The two-week pilot experiment experienced only moderate storms (H_s up to 2.5m offshore), and provided good data for the hydrodynamic parameters, but little morphodynamic change. By contrast, the six-week main experiment experienced continuous major storms, with offshore H_s of up to 5m, which resulted in very substantial changes in morphology but caused logistical problems with data gathering; nonetheless, a very comprehensive data-set of these extreme conditions was collected.

In the Egmond main experiment eight consortium partners obtained data over a six-week period in October – November 1998 as follows:

- water-levels at 15 locations
- wave heights and periods at 18 locations
- current speed and direction at 14 fixed and 1 roving locations
- sediment concentration/transport at 1 fixed and 1 roving location
- bed material (grab) at 125 points
- bedforms by sidescan and altimeter surveys, and 2 ripple profilers

- repeat bathymetric surveys of beach, nearshore and offshore
- fluorescent tracer measurements
- ARGUS images of wave-breaking over bars
- X-band radar images of wave propagation
- meteorological parameters

Teignmouth

The second two experiments took place at Teignmouth on the south coast of England (see map at front of Volume) in spring and autumn 1999 (Whitehouse et al, 2000; Whitehouse and Sutherland, 2001). A rocky headland and a river mouth provide a strong three-dimensionality to the coastline and bathymetry, which in turn result in complex patterns of flow and waves. Groynes, a seawall and a pier are constructed on the beach fronting the town. A complicated re-curving spit adjacent to the river mouth, and a series of offshore sandbanks, are very active morphodynamically. The macro-tidal range and currents dominate the dynamics of this east-facing site, which experiences smaller waves than at Egmond, although a storm can quickly alter the beach. The grain sizes are very variable, with fine sand offshore, medium sand on the beach and banks and very coarse material in the deep channel where tidal currents reach 2 m/s.

During the two-week pilot campaign a moderate storm at the start was followed by a long period of calmer weather when good tidal current data was collected. The six-week main campaign was characterised by a succession of storms with calms in between. This enabled good wave data to be collected as well as providing periods of calm for surveys and tripod servicing to be performed. There were extensive changes in the nearshore morphology during this campaign.

In the Teignmouth main experiment six consortium partners obtained data over a six-week period in October – November 1999 as follows:

- water-levels at 31 locations
- wave heights and periods at 26 locations (22 directional)
- current speed and direction at 27 locations, plus float tracking
- bed-mounted and vessel-mounted Acoustic Doppler Profilers
- sediment concentration/transport at 14 locations
- bed material (grab) at 50 offshore points and many intertidal points
- bedforms by sidescan survey, altimeter and ripple profiler
- scour monitors at 3 locations on the beach
- repeat bathymetric surveys of beach, nearshore and offshore
- ARGUS images of wave-breaking and waterline over sandbanks
- X-band radar images of wave propagation
- meteorological parameters and water temperature

American researchers collaborated in the field measurements at both sites, under the auspices of an ONR NICOP project. ARGUS cameras (which are still operating) were deployed by Oregon State University at both Egmond and Teignmouth to monitor the long-term changes in morphology, as visualised through wave breaking. The small-scale bedforms were surveyed over the Egmond site by the Naval Postgraduate School at Monterey, using an array of ultrasonic altimeters mounted on the WESP.

3. MODELLING

The data from the experiments at both sites allowed comprehensive tests to be made of the hydrodynamic and morphodynamic numerical models. Numerical modellers worked interactively with the experimenters, at the planning, experiment, and evaluation phases. Very successful "Modellers' Weeks" were held at both sites during the experiments, when the project's modellers, supplemented by others from outside the project, ran their models together at the site they were modelling.

Coastal Profile models, in which a vertical slice perpendicular to the coast is modelled to predict the cross-shore variation in wave heights, currents, sediment transport and morphological evolution, are commonly used on straight uniform beaches. Five different Coastal Profile models were used by the COAST3D modelling partners (Delft Hydraulics, HR, CIIRC and Universities of Utrecht and Liverpool) to simulate the hydrodynamics and morphodynamics of the beach at Egmond. However, it was recognised that the 2.5D nature of the beach might be sufficiently non-uniform that the model assumptions might be invalid. Consequently, modellers from Delft Hydraulics and a visitor to the Modellers' Week from University of Delaware also applied 2DH Coastal Area models.

The greater irregularity of the coastline at Teignmouth required the use of Coastal Area models, in which the spatial distribution of waves, currents, sediment transport and morphological evolution are modelled over a horizontal 2DH grid. Such models demand much longer run-times and greater complexity of setting up and calibration than Coastal Profile models. Four partners (HR, Delft Hydraulics, CIIRC and University of Liverpool) applied their Coastal Area models to the Teignmouth case. This site, which has a wide range of grain-sizes, stretches the capabilities of present day coastal morphodynamic numerical models to their limits, and provides a very exacting test of these and future models. A greater depth of analysis and modelling has been possible to date for Egmond than for Teignmouth, because the work there commenced one year earlier.

4. RESULTS

The data from the experiments have yielded a wide range of interesting results, only a few of which are touched on in this paper.

Experiments at Egmond

At the notionally uniform site at Egmond, analysis of the bathymetric changes during the autumn experiment revealed that the bed changes associated with the along-shore non-uniformity were actually greater than those associated with along-shore uniform behaviour, so that an assumption of 2D behaviour would not be appropriate (Ruessink et al, 2000). Shear waves and edge waves are an important feature here, and were analysed by Miles et al, 2000. A side-scan sonar survey revealed a complex distribution of rippled areas, smooth areas, and more irregular bed features (Lankneus et al, 1999). Detailed measurements in the swash-zone show that this is a very active area, responding to infragravity wave activity, and moving mainly during the beginning of the flood period (Degryse et al, 2000, Degryse Kulkarni et al, 2001). An in-depth analysis of the interpretation of the data from Egmond (Van Rijn, 2000) obtained the following results:

- During major storms the nearshore wave height is strongly modulated by the tidal level over the bars, and the nearshore significant wave-height is typically about 50% of the offshore value as a result of refraction, friction and breaking
- The maximum significant wave height saturates at about 0.7 of the instantaneous water depth in the outer zone, but further inshore over the inner bar this value is reduced to 0.4 to 0.5
- The onshore orbital velocity (under wave crests) can reach values of 1.5 times the offshore orbital velocity (under wave troughs) around the crest of the inner bar. The net effect is to drive sediment onshore.
- The currents are strongly affected by tide, wind and wave-driven processes
- Long-shore currents increase from 0.5 m/s (tidal) in calm conditions up to 2 m/s (with wind and waves) in storm conditions. These will drive sediment alongshore and contribute to changes in beach planshape.
- Offshore-directed cross-shore currents (probably under-tow rather than rip) of up to 0.65 m/s were observed under storm conditions. These will carry sediment offshore.
- Bed material is coarser in bar troughs than on crests, by a factor of almost 2
- Small-scale bed-form activity is most pronounced on the seaward flanks of bars. This affects the bottom roughness, which in turn affects sediment suspension.
- Sand transport is dominated by suspension in storm conditions, giving a maximum observed long-shore transport of 30,000 m^3 per day and cross-shore transport of 25 m^3 per m width per day off-shore directed due to undertow and rip currents
- The bars, which were almost straight and uniform just after a storm at the start of the experiment remained fairly straight through the measured storms, but became sinuous and dissected by rip-channels in the calmer period after the storms
- The beach volume is almost continuously adjusting towards a new equilibrium if the bar crest level is changing; volume changes between 1 and 3 m^3 per m width per day were observed under storm conditions
- The beach volume responds strongly to the crest level of the inner bar, but with a considerable time lag, accreting after the crest is high and eroding after it is low.

The detailed scientific results of all the partners involved in the Egmond experiments are given by Hoekstra et al (2001). The main conclusions are listed in Section 8 of the present paper.

Experiments at Teignmouth

The results of a similar in-depth analysis of the data from Teignmouth are being drawn together into a set of themed interpretation papers, to form a special issue of the new journal "Nearshore and Coastal Oceanography" with the title: Sediment transport and morphodynamics on a complex coastline. The papers each synthesise results from several institutes covering the following subjects:

1. Coastal and nearshore morphology, bedforms and sediment transport pathways (Van Lancker, Lanckneus, Moerkerke, Hearn, Hoekstra, Levoy, Miles and Whitehouse)
2. Surf zone processes and sediment transport on a macrotidal mixed-sediment beach (Miles and Russell)
3. Morphodynamic behaviour of the swash zone (Degryse Kulkarni, Levoy, Monfort and Miles)
4. Bedform migration and sediment transport on an intertidal shoal (Hoekstra, Bell, van Santen, Roode, Levoy and Whitehouse)
5. The spatial and temporal response of beach and seabed levels on a macro-tidal coastline (Whitehouse, Levoy, Miles, Sutherland and Waters)

The main conclusions are listed in Section 8 of the present paper. Some specific results can be given. A sidescan survey showed a complex pattern of bedforms, which, when taken together with grainsize trends, allowed the sediment transport pathways to be deduced. The swash-zone was found to be very active morphodynamically, showing rapid accretion and erosion of the bed as the tide rose and fell. Measurements of ripple profiles taken acoustically in the strong estuarine outflow and inflow show a rapid migration and reversal of asymmetry, enabling bedload transport rates to be calculated. At the same location, an acoustic backscatter system shows sand suspended strongly, although suspension is probably a rare event over much of the study area. Sidescan observations of tubeworm patches confirm that the bed is much less mobile in the deeper water offshore of the very active beach and sand bank system.

Water levels, waves, currents and turbidity at two sites, one at a nearshore location and one in the estuary mouth, were continuously monitored for 12 months, and the results were analysed and reported by Sutherland et al (2001a).

Databases

The experiments have resulted in a large amount of high quality data, which, following stringent quality and consistency checks, have been incorporated into data-banks for Egmond (Vermetten, 1999; Vermetten et al, 2001) and Teignmouth (Whitehouse and Sutherland, 2001).

Modelling at Egmond

Coastal Profile models were run initially for a pre-existing data-set with significant morphology changes, and the pilot experiment at Egmond, when there was very little morphological change. The predictions of wave-heights, set-up and long-shore currents showed large differences between models. Results of the modelling for the Egmond site were described by Brady and Sutherland (2001), O'Connor and Nicholson (1999), Tomé et al (1998) and Walstra et al (1999).

The Profile models have been run during the main experiment when large changes in morphology occurred. Three types of run were performed to produce:

- Time-series of wave heights and velocities along the main transect
- Cross-shore profiles of wave heights and currents
- Bathymetric updating of longshore-averaged bathymetry

Quantitative methods for establishing the quality of model performance have been established for wave height, currents and morphology (Brady and Sutherland, 2001; Van Rijn, 2001). The offshore movement of the bars during the main storm was modelled well, but model performance for morphology was less good for lower wave heights. Coastal Area models run for the Egmond site predicted circulation cells and rip systems (Elias et al, 2000).

The results of the Coastal Profile modelling are synthesised in a multi-institute journal paper (Van Rijn et al, 2001). The main conclusions are listed in Section 8 of the present paper.

Modelling at Teignmouth

At the complex Teignmouth site the current-meter data showed large pulses as vortices are produced at the edge of the jet emerging from the estuary mouth. Some of the Coastal Area models are also able to predict such vortices, with at least qualitatively the right features (Hall et al, 2001; Van Ormondt, 2000). The availability of a relatively large number of measurement points around the mouth of the estuary allowed the models to be calibrated and assessed thoroughly. The models predicted the complex flow patterns caused by a spring tide well. Agreement was also reasonably good for the more complicated case of the modelling of a storm, when wave-induced currents formed a number of additional gyres in shallow water. The autumn experiment at Teignmouth, as at Egmond, encountered storms that produced large changes in the bathymetry that provide the morphological models with good data to simulate.

The results of the Coastal Area modelling are synthesised in a multi-institute journal paper (Sutherland et al, 2001b). The main conclusions are listed in Section 8 of the present paper.

5. INNOVATIVE MEASUREMENT TECHNIQUES

Many of the measurement techniques used in the experiments were at the cutting edge of technology, and the project provided a good testing ground for them. Some of these techniques will no doubt become available in due course for measurements and monitoring of coastal sites for practical projects. The experiences with some of them are given below.

The WESP amphibious vehicle and the CRIS instrumented trailer, constructed and operated by the Rijkswaterstaat, both worked well at Egmond. The WESP provided a versatile and relatively weather-independent bathymetric surveying system, particularly suited to frequent repeat surveys. It also proved invaluable for deploying and recovering other instrument systems. The CRIS provided a unique roving sediment transport measurement system, with the ability to measure velocities and sand concentrations at accurately known heights within the crucial layer near the bed. However, the WESP and CRIS were too difficult and expensive to transport to the Teignmouth site, where more conventional techniques were used instead.

Novel acoustic techniques were deployed by POL. Their Acoustic Backscatter System gathered suspended sediment concentration and grainsize data with very high spatial and temporal resolution from a fixed tripod at each site. Like the CRIS, the nearbed resolution fills a gap left by more conventional instruments. An Acoustic Ripple Profiler enabled detailed analyses of the variations in ripple height, wavelength and migration speed to be measured, allowing bedload transport to be calculated. An array of acoustic altimeters was deployed from the WESP by the US Naval Postgraduate School enabled the distribution of small-scale bedform heights at Egmond to be mapped. This complemented the sidescan measurements of bedform wavelength and orientation mapped by MAGELAS. Small-scale bedforms play an important role in determining the bottom friction and sediment transport distributions.

Two complementary wave-mapping techniques were used at both sites. ARGUS cameras deployed by Oregon State University with Universities of Utrecht (Egmond) and Plymouth (Teignmouth) show the wave-breaking pattern hourly over several years. This locates the shifting positions of sand bars and sand banks. At Teignmouth the sandbanks themselves could be seen at Low Water Spring

Tides. An X-band radar deployed by POL for the 6-week autumn experiments at each site provided hourly measurements of the pattern of wavelengths and directions. Highly innovative and computer-intensive analysis techniques were devised to derive the maximum interpretation from the radar data, which can also be used to deduce bathymetry. The time-averaged radar images have strong similarities with the time-averaged visual images from the ARGUS cameras, and an intercomparison exercise has been undertaken (Ruessink et al, 2001b).

Innovative and complementary measurements of swash-zone processes were made by the Universties of Caen, Utrecht and Plymouth. This hitherto little explored zone plays a major role in sediment transport. Results from this cutting-edge research will, when mature, be incorporated into practical models.

Other innovative methods, including the multi-instrumented tripods, the University of Caen's remote-controlled video plane, Caen's DGPS Quad-bike surveys, and HR's scour monitors, are described elsewhere.

6. CZM TOOLS

An important aspect of the consortium is that national regulatory authorities from UK (Environment Agency, in conjunction with MAFF) and NL (RIKZ/Rijkswaterstaat) were partners, who ensured that the project focused on practical tools for Coastal Zone Management (CZM) as well as purely scientific results. The means by which results from the project can be made use of in CZM applications were addressed from the outset of the project. It was found to be by no means straightforward: there is a gap between the problem-driven requirements of CZ Managers and the science-driven goals of the researchers. All partners were keen to find methods of bridging this gap. To aid this, the consortium partners each completed a questionnaire addressing CZM issues in terms of the results that their data analysis and/or modelling can provide. Their responses have been used as the basis for detailed appendices in a report on the selection of CZM tools aimed at assisting coastal managers (Mulder et al, 2001).

A summary of the research findings of the COAST3D project from a user perspective, and comments on the researcher/user interface, is given by Rawson et al (2001).

7. DISSEMINATION AND EXPLOITATION

The COAST3D project has provided the following products, some freely available and some available commercially:

- **Data-sets:** from the two sites, available publicly on CD-ROMs in October 2001
- **Reports and papers:** on coastal processes, morphological models, and innovative instrumentation
- **CZM tools and guidelines:** a report describing *when* to use *what* tools and *how* to use these tools, illustrated by case studies at Egmond and Teignmouth
- **Models:** validated morphodynamic numerical models
- **Instruments:** innovative instrumentation and systems for measuring bathymetry, waves and sediment transport

A Technology Implementation Plan has been prepared, defining the exploitable products, the nature of the exploitation, and who will undertake each activity in the years following the completion of the project. This includes promotion of the report "Guidelines on the Selection of CZM Tools" (Mulder et al, 2001) within the national regulatory authorities of Rijkswaterstaat (NL), and MAFF and the Environment Agency (UK).

Dissemination of the results of the project include:

- papers presented at conferences, particularly the International Conference on Coastal Engineering, (Sydney, July 2000), the EurOCEAN 2000 conference (Hamburg, Aug/Sept 2000), the MAFF Conference of River and Coastal Engineers, and the Coastal Dynamics 2001 conference mentioned below
- papers in scientific journals, listed in the Project Publication List
- Special Issue of the journal Nearshore and Coastal Oceanography devoted to papers from the COAST3D Teignmouth Experiment
- posters displayed at conferences in Lisbon and Hamburg, and by partner organisations and funders
- leaflets made publicly available describing the project in general, and separate leaflets and posters to inform the public at the two experiment sites
- newspaper, TV and radio articles locally in the area of the two experiments
- the Final Workshop, which was well attended by both researchers and end-users external to the project

Papers presented at the 27th ICCE in Sydney included model validation (Elias et al, 2000), and process interpretation (Miles et al, 2000), both for Egmond. The latter paper involved multi-institute collaboration between the Universities of Plymouth, Utrecht and Caen and the US Naval Postgraduate School.

An additional show-case after the end of the project is the Coastal Dynamics conference in Lund, Sweden, at which seven papers describing scientific results from the COAST3D project will be presented by various of the partners. The following papers will be published in the conference proceedings (CD '01, 2001):

- Soulsby presents an overview of the COAST3D project
- Van Lancker et al discuss sediment transport deductions from their experimental work at Egmond
- Hoekstra et al discuss results concerning hydrodynamics, intertidal dunes and bedload transport from their measurements at Teignmouth

- Grasmeijer and Van Rijn present field data and model results investigating the influence of bed forms on suspended sediment concentration/transport at Egmond
- Klein et al present results from numerical modelling of rip currents at Egmond
- Kleinhout et al compare results of two Coastal Profile models of the hydrodynamics and morphological changes at Egmond
- Walstra et al present hydrodynamic validation results from Coastal Area models of Teignmouth from two institutes.

8. CONCLUSIONS

At the outset of the COAST3D project a number of fundamental questions concerning beach and nearshore hydrodynamics and morphodynamics were asked. These can now, as a result of the research activities of the project, be answered. The conclusions given here are largely drawn from the Synthesis Papers A9, B7, C8 and D5, and these papers both elaborate on these conclusions and give references to more detailed results in other papers in the present Volume and other publications resulting from COAST3D.

Conclusions regarding physical processes

The following questions (Q) and conclusions (C) are drawn from the experimental work at Egmond. The answers are elaborated in Synthesis Paper A9 of this Volume, drawing on material from Papers A2 to A8. The conclusions given for Egmond are taken to be applicable to similar quasi-straight micro/meso-tidal sandy coasts around Europe.

Q1: Is the Egmond 2.5D morphological system sufficiently alongshore uniform to capture the morphological changes in a single or limited number of cross-shore profiles?

C1: No, on the time scale of the experiment, beach and surf-zone morphology were gradually transformed from initial alongshore rather uniform systems into highly 3D systems with an oblique outer bar, a crescentic inner bar in relation to the development and migration of a mobile rip channel and the alongshore non-uniform behaviour of beach profiles.

Q2: The Egmond 2.5D experiment was implemented during a period characterized by a sequence of storms and heavy storms. Does this result in a significant loss (or gain) of sediment?

C2: No, the measured morphological developments suggest that in spite of the high energetic conditions during the field campaign little or no net sediment was lost from the research area in either a longshore or offshore direction.

Q3: Are there hydrodynamic and sediment transport processes that even in case of a simple and straight uniform coast result in a 3D pattern of water- and sediment fluxes?

C3: Yes, longshore current oscillations (shear waves) develop in the intertidal and subtidal zone, even for a straight uniform coast. The shear waves in the intertidal zone affected both sediment suspension and sediment transport. The result is a migrating 3D-transport pattern along the beach or coast.

Q4: How important are alongshore versus cross-shore processes for sediment fluxes and morphological changes in the intertidal and (shallow) subtidal zone and for the period considered?

C4: Local daily changes in beach volumes in relation to the measured onshore sediment transport rates indicate that the morphological changes in the cross-shore profile cannot simply be explained by gradients in cross-shore sediment transport rates. A longshore redistribution of sediment is probably equally important or even dominates the local sediment budgets.

Q5: What is the role of bedforms and grain sizes for sediment transport in the nearshore zone?

C5: There appears to be a great variety of bedforms in the nearshore zone which results in a great variability in bed roughness. The range in bedforms also results in an important feedback for suspended sediment transport processes in the presence of waves.

Q6: What are important processes for beachface development and accretion (or erosion) of the beach?

C6: Swash processes appear to be important due to swash bar formation and migration. Swash bar dynamics is partly related to infragravity energy, in combination with tidal levels.

Q7: Is the Egmond type of coastal system sufficiently uniform in the alongshore direction to explain morphological changes in terms of 2D cross-shore processes?

C7: No, the morphological system acts as a 3D system on the time-scale considered (6 weeks). However, from previous studies it is known that on the time scale of years the morphological system shows 2D behaviour.

The following questions and conclusions are drawn from the experimental work at Teignmouth. The answers are elaborated in Synthesis Paper C8 of this Volume, drawing on material from Papers C1 to C7. The conclusions given for Teignmouth are taken to be applicable to similar irregular coasts with headlands and/or inlets around Europe.

Q8: What can be learnt about patterns of sediment movement from the evidence of the sediments and bedforms themselves?

C8: The deduced sediment transport vectors demonstrated the importance of wave driven processes and tides as well as the locally strong influence of the estuary outflow in moving sediment in the near-shore zone. The sediment fined rapidly across the seaward end of the ebb tidal shoal towards deeper water, reflecting the preferential deposition of coarser material in the shallower water. The presence of three lobes of sediment reflected the historical movement of the approach channel. In the deeper water the bed sediment is mobile less often and this is confirmed by side-scan observations of tubeworm colonies.

Q9: What differences in wave and current behaviour can be detected between the uniform (North) transect and the highly non-uniform transect (South)?
C9: Wave transformations at the North and South transects were investigated using data from offshore locations and on the beach. At the South, the ratio of inshore wave height to offshore wave height varied between 0.2 and 1.2, with the lower values occurring during periods of high wave activity, and there was a clear tidal modulation of inshore wave height. Less energy arrived at the beach than for the equivalent data from the North transect, thus demonstrating the increased role of the shallow near-shore morphology in dissipating wave energy. A regional picture of wave transformation was provided by the X-band radar.

Q10: How do sediment transport rates vary across the surf zone?
C10: The magnitude of the sediment transport increased shorewards through the surf zone, to a maximum in the inner surf zone. The net transport was related to a balance between the wave asymmetry (driving sediment onshore) and the undertow (mean current, driving sediment offshore).

Q11: How sensitive is longshore sediment transport to wave direction?
C11: The direction of the longshore current on the beach was found to correlate with changes in the offshore wave direction. For waves approaching the shore at angles less than 140ºT the wave-induced longshore current at the beach was to the south. For waves approaching at larger angles than this the current was to the North. The magnitude of the current depended on the wave height and cross-shore location.

Q12: How does the beach respond to wave attack?
C12: The influence of the waves on beach response and overtopping of the seawall depends on the phasing of waves and the tidal level. The level of the beach in front of the seawall in the centre of the study area became very low exposing the sheet piling. The longshore transport of sediment into this area from the north replenished the beach level.

Q13: How do swash processes determine beach accretion and erosion?
C13: Data for the swash zone showed that the hydrodynamic conditions, water table, beach slope and grain characteristics had a significant influence on the bed levels in the swash zone. The swash-zone was found to be very active morphodynamically, showing rapid accretion and erosion of the bed as the tide rose and fell. The detailed composition of the beach sediment changed both within and between tides. Depending on the wave conditions the beach face showed net accretion or erosion. Monitoring of the swash zone morphology showed that the bed level varied by up to 0.4m during the tide. The net change between tides was typically less than this.

Q14: What information can acoustic techniques yield about sediment transport rates?
C14: An acoustic ripple profiler showed a rapid migration of the bedforms with the tidal current and reversal of asymmetry with flow direction. Bedload transport rates were calculated from the bedform migration rate and bedform characteristics. An acoustic backscatter system showed sediment suspension "events" in the lowest 0.5m of the water column above the bedforms.

Q15: What do the various bathymetric survey techniques reveal about the patterns of bed level change, ranging from the beach to the offshore areas?
C15: Long-term beach profile data showed that between 1995 and 1999 the bed levels had on average become lower in the centre of the study area. The periodic attachment of banks to the beach led to increased volumes of beach material at the annual scale, and beach levels were highest during 1997. Intertidal topographic surveys showed down-cutting of the low tide terrace. On the upper part of the beach the development alongshore occurred in alternating zones of erosion and accretion of up to 0.75m. Surveys adjacent to the main estuary outflow showed variations in average bed level of 0.3m. The bedform population here varied in wavelength between 0.5 and 1.7m and in height between 0.03 and 0.11m. The vessel-based bathymetric surveys between 1998 and 1999 showed that the region around the near-shore banks was the most active, with zones of erosion and accretion of up to 1.4m. Most morphological change occurred where the bed was above the -0.5mCD contour; in areas deeper than this only patchy erosion and deposition occurred.

Many of the questions and conclusions have important implications for CZM. For example, it has been assumed conventionally that the biggest changes in beach volume occur in response to major storms. This has led to a concentration on modelling of major storms as part of practical coastal zone management studies. But conclusion C2, indicating little change in beach volume despite a succession of large storms, suggests that this may not be an adequate approach.

Another outcome of the experimental work that has implications for modelling addresses the question of when it is appropriate to use a 2DV Coastal Profile Model (CPM), and when it is necessary to use a full 2DH or 3D Coastal Area Model (CAM). CPMs are relatively simple and cheap, whereas CAMs have greater costs for setting up, validating, and calibrating the model, and much longer computer run times. Paper A4 and Ruessink et al (2001a) propose a nondimensional metric obtainable from bathymetric data that offers a criterion for this decision based on the observed behaviour of the long-shore current. If the Bathymetric Nonuniformity Measure $\chi^2 < 0.02$ then 3D effects are weak and a CPM is valid, whereas if $\chi^2 > 0.02$

then 3D effects are strong and a CAM is required. Different threshold values of χ^2 may be more appropriate for features other than the long-shore current.

Conclusions regarding modelling
The primary question concerning the modelling work is how well the models are able to simulate the observed spatial and temporal variations in waves, currents, sediment transport and morphological change. These are the natural changes observed over the period of six weeks of the Main Experiment at each site. If the models simulate these changes accurately, then it is inferred that they will also be able to simulate changes that would result from man-made projects and interventions. An innovative feature of the tests was the use of quantitative measures of model performance, rather than the subjective qualitative judgements that are more often used.

The following conclusions, taken from Paper B7 and based on Papers B1 to B6, were reached about the ability of deterministic and probabilistic Coastal Profile Models to simulate the hydrodynamic and morphodynamic processes on the time scale of storms for "2.5D" straight sandy coasts, based on the Egmond modelling:

- Profile models can quite accurately (errors smaller than 10%) represent the significant wave height distribution along the surf zone, if the wave breaking model is properly calibrated; the wave breaking coefficient should be a function of local wave steepness and bottom slope for most accurate results.
- Profile models can simulate the longshore and cross-shore currents in 3D field conditions only in a reasonable way with relative accuracies of 30% to 50%; Profile models including cross-shore mixing effects and breaker delay effects do not produce better predictions of the longshore and cross-shore current velocities.
- Profile models yielding good results for hydrodynamics do not automatically yield good results for morphodynamics; often additional calibration using measured bed profile changes is required to obtain good morphodynamic results; the calibration coefficients involved are not proven to be site-independent.
- Profile models can (after proper calibration) simulate the behaviour of the outer and inner bars on the storm time scale in a quite reasonable way; the behaviour of the beach can not be modelled with sufficient accuracy on the storm time scale.

Overall, it can be concluded that Profile models can simulate the behaviour of the outer bar system quite well on the time scale of storms. This encouraging result offers a good opportunity to study the behaviour of shore-face nourishments (feeder berms), which are most often situated in the outer bar region for practical reasons (draft of dredgers). The simulation of the behaviour of the inner bar on the storm time scale is somewhat less good due to the presence of 3D effects and the absence of a clear net migration of the inner bar on these time scales.

The following conclusions, taken from Paper D5 and based on Papers D1 to D4, were reached about the ability of Coastal Area Models to simulate the hydrodynamic and morphodynamic processes at complex irregular sites, based on the Teignmouth modelling:

- Coastal Area Models are able to predict tidal flows at a complex site well.
- The modelling of currents induced by wave breaking and tides is more difficult, but many of the features are modelled, albeit not perfectly. Small errors in predicting the position or strength of vortices leads to large errors in time series measured at a point.
- The models rely on good boundary conditions that required the use of calibrated regional models.
- Model performance statistics have been used to help in the objective assessment of model performance. A Relative Mean Absolute Error of 0.6 represents a good result from a tuned model
- Most models are limited to using a single grain size. This means that at a complex site, such as Teignmouth, the entire area cannot be modelled in a single model run. More work is needed on the modelling of beaches with a variety of grain sizes as the effect of sediment grading is appreciable.
- The main features of the bed changes north of the channel were modelled well using a single grain size over a 14 day (spring tide to spring tide) period.

The last conclusion, namely the relatively good performance of a CAM in predicting changes in the morphology of the outer banks at Teignmouth over a 14-day period demonstrated in Paper D3, has significance for CZM purposes. However, the question of the best method of extending such predictions to periods of years is still open.

A surprising conclusion from the modellers was that in some ways it was easier to perform 2DH Coastal Area modelling for Teignmouth than for Egmond. Unexpectedly, considering the greater complexity of the Teignmouth site, better agreement was found with the hydrodynamic data for Teignmouth than Egmond. One might speculate that this is because the non-uniformities at Teignmouth are produced largely by the hard geology and structures and hence are permanent, whereas at Egmond they are self-generated by the sediment and ephemeral.

9. SUMMARY

Four major field measurement campaigns have been successfully completed, two on the coast of the Netherlands and two on the south English coast. These have resulted in a very large amount of high quality data, which have been incorporated into publicly available data banks. Numerical modellers have gathered at both the sites to participate in

"Modellers' Weeks", boosted by modellers external to the project. The work done in these events, together with a much larger effort when back at base, has made good use of the data to test and intercompare the models' capabilities for predicting the distributions and evolution of waves, water-levels, currents, sediment transport and bed morphology at the two sites. The data has been used by the experimenters to derive a better understanding of the processes involved, which can subsequently be used to develop the numerical models further, as well as providing important information in its own right. The results from the data and the modelling, together with an assessment of the new monitoring techniques used, have been converted into a form that is of direct use for coastal zone management. Only a fraction of the wealth of results emerging from the project is included in this overview paper. Further details of results are presented in the other papers in this Volume.

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