Department for Environment Food & Rural Affairs

Environment Agency

delivering benefits through evidence

Beach modelling: Lessons learnt from past scheme performance

Project: SC110004/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

The Environment Agency is the leading public body protecting and improving the environment in England.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned by the Environment Agency's Evidence Directorate and funded by the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management Research and Development Programme.

Published by:
Environment Agency, Horizon House, Deanery Road, Bristol, BS1 5AH

www.environment-agency.gov.uk

ISBN: 978-1-84911-313-7

E: enquiries@environment-agency.gov.uk.

Author(s):
K A Burgess, A P R Frampton, A P Bradbury

Dissemination Status:
Publicly available

Keywords:
beach, lessons, modelling, performance, review, scheme, waves

Research Contractor:
Halcrow, a CH2M Hill company
Ash House, Falcon Road, Sowton, Exeter, Devon EX2 7LB

Tel. 01392 444 252

Environment Agency's Project Manager:
Andy Tan, Evidence Directorate

Theme Manager:
Stefan Laegar, Modelling and Risk R&D Theme

Collaborator(s):
Channel Coastal Observatory
Herrington Consulting Ltd
Coastal Engineering UK Ltd

Project Number:
SC110004

Evidence at the Environment Agency

Evidence underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us, helps us to develop tools and techniques to monitor and manage our environment as efficiently and effectively as possible. It also helps us to understand how the environment is changing and to identify what the future pressures may be.

The work of the Environment Agency's Evidence Directorate is a key ingredient in the partnership between research, guidance and operations that enables the Environment Agency to protect and restore our environment.

This report was produced by the Scientific and Evidence Services team within Evidence. The team focuses on four main areas of activity:

- **Setting the agenda**, by providing the evidence for decisions;
- **Maintaining scientific credibility**, by ensuring that our programmes and projects are fit for purpose and executed according to international standards;
- **Carrying out research**, either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available.

Miranda Kavanagh

Director of Evidence

Executive summary

Beach management including recharge and recycling is a commonplace activity as part of the UK's coastal flood and erosion defence provision. Decisions on development of such schemes are often informed by beach modelling including numerical, physical and empirical approaches.

This report aims to improve understanding in this area by looking at previous schemes. The research has investigated the lessons that can be learned from the actual performance of schemes compared with original model expectations by reviewing case studies for 11 sites and drawing upon anecdotal information gathered through engagement with industry practitioners.

This process has identified a range of considerations that should be taken into account when beach modelling is being considered or undertaken. It is aimed at commissioning organisations who are planning to develop a beach scheme or undertake beach management as part of their coastal flood or erosion rick management practices who may not have detailed technical knowledge of beach modelling approaches.

This report presents a range of findings on the application of beach modelling, with guidance on how to better deal with these issues in the development of future schemes.

Some of the common themes and main findings include:

- The physics of beach models are generally sound; it is the interpretation and application of those models together with the data used in them where attention needs to be focussed, as set out in this report.
- Beach models are simplified representations of beach processes and it is usual for a series of models to be used in combination to develop a beach scheme; rarely is a design based solely on one model type. Outputs of these are invaluable to help design and manage beach schemes but they alone do not provide the definitive answers. Coastal engineering knowledge and expertise to effectively understand and combine the outputs from these different tools are imperative.
- Often, what is implemented is not what was modelled, including the size and/or grading of the beach nourishment material itself, so the beach inevitably behaves differently from that predicted. Despite this, beach models are rarely re-used to examine changes in these factors to reassess likely performance or potential improvement to the beach management regime.
- Use of models for sensitivity testing and scenario assessment, as well as post-project re-modelling, could provide effective tools to deliver more effective and efficient beach management.
- A difference in wave climate is commonly a fundamental cause of the difference between actual and predicted beach performance. Good representation of wave climate and accurate wave modelling are therefore critical components of the beach modelling process.

This report explains these and other points in greater detail, identifying the lessons than can be learned and offering guidance on how these might be considered and overcome in the future.

This should lead to more appropriate application of beach modelling tools and use of the outputs they generate as part of the overall suite of information required to plan and

deliver sustainable beach management solutions in the future. This should lead to more appropriate application of beach modelling tools and use of the outputs they generate as part of the overall suite of information required to plan and deliver sustainable beach management solutions in the future.

Acknowledgements

During the project, consultation was undertaken with the following individuals as part of initial discussions, meetings and wider workshops held in January and November 2012. Several people on this list also made valuable contributions to the case studies or provided other information which has been used by the project.

Name	Organisation
Alan Brampton	HR Wallingford
Alan Frampton	Halcrow, a CH2M Hill company
Alan Williams	Coastal Engineering UK
Andy Bradbury	Channel Coastal Observatory
Andy Parsons	Halcrow, a CH2M Hill company
Andy Tan	Environment Agency
Anne Thurston	Environment Agency
Ben Carroll	ABPmer
Bryan Curtis	Worthing Borough Council
Carl Green	Wyre Borough Council
Chris Hayes	Environment Agency
Clare Wilkinson	Channel Coastal Observatory
Darren Price	Halcrow, a CH2M Hill company
Dominic Reeve	University of Swansea
Hakeem Johnson	Halcrow, a CH2M Hill company
Helen Jay	Halcrow, a CH2M Hill company
Ian Thomas	Pevensey Coastal Defences
Jack Eade	Channel Coastal Observatory
Jackson Harris	Channel Coastal Observatory
John Pos	URS
Jon Kemp	HR Wallingford
Jonathan Rogers	Halcrow, a CH2M Hill company
Kevin Burgess	Halcrow, a CH2M Hill company
Malcolm Bray	University of Portsmouth
Mike Stickley	Halcrow, a CH2M Hill company
Neil Watson	Environment Agency
Nigel Pontee	Halcrow, a CH2M Hill company
Paul Canning	Atkins
Robert McCall	University of Plymouth
Roger Spencer	Arun District Council
Sam Cope	Channel Coastal Observatory
Sam Box	Halcrow, a CH2M Hill company
Sam Grootveld	Environment Agency
Simon Herrington	Herrington Consulting
Suzana Ilic	University of Lancaster
Ted Edwards	Canterbury City Council
Tim Poate	University of Plymouth
Travis Mason	Channel Coastal Observatory
Uwe Dornbusch	Environment Agency

Contents

List of Tables

List of Figures

1 Introduction

1.1 Aim of this report

Beach management (for example, recharge and recycling) accounts for several million pounds of the UK's coastal flood defence capital and maintenance expenditure each year. Decisions on the development of such schemes are often informed by beach modelling, including numerical, physical and empirical approaches. By looking at previous schemes this report aims to improve understanding about the performance of different modelling approaches.

1.2 Who is this report for?

The report is for coastal practitioners and those in commissioning organisations who may not have detailed technical knowledge of beach modelling. It identifies points for them to be critically aware of when beach modelling is being contemplated or carried out. The report should also help readers gain a better understanding of the approach to modelling, the decisions that need to be taken along the way and the outputs from modelling.

1.3 Approach taken

The project compared the actual performance of schemes with original model expectations by reviewing a number of case studies covering a wide range of beach types, modelling approaches and timescales from around the UK.

The report identifies lessons and advice from data comparison and anecdotal evidence that should help to achieve better use of modelling tools for beach scheme design and management in the future. However, it is not intended to be the exhaustive examination of, or detailed guidance for, all aspects of modelling or beach design.

The information contained in this report should therefore be considered alongside other guidance, in particular:

- *Beach Management Manual* (CIRIA 2010)
- *Flood and Coastal Risk Management Modelling Strategy 2010-2015* (Environment Agency 2010a)

These two publications expand on the types of methods used in these case studies and other approaches that practitioners might consider. Although this report does not repeat the contents of this other guidance, the information has been drawn upon and used to develop and support the findings provided here.

1.4 Structure of this guidance

Section 2 contains a summary of the main lessons from the assessments, providing readers with ready access to key points to consider. Section 3 briefly describes the characteristics of each case study, with further detail given in the Appendix. Section 4 presents more fully the lessons learned from the case studies with respect to approaching beach modelling in the future.

Sections 5 to 9 provide a brief generic overview of different types of modelling tools and techniques that were applied in the case studies, while Section 10 provides advice on the use of wave data for beach modelling. These sections also include any additional specific direction on the use of these methods from observations made during the case studies and anecdotal information gathered during the study.

Throughout the document reference is made to individual case studies to signpost readers to where to find out more on a particular observation or finding. Note that these are merely an illustration and should not be considered as necessarily exclusive to those individual cases.

A separate project technical report provides supporting information, summarising the project approach including, for those interested in the finer details, the full case study assessments.

2 Summary findings

This section summarises the main points and lessons arising from the comparison and analysis of past and predicted beach behaviour at 11 sites (Section 3) and other information gathered through the course of this study. It therefore provides a quick reference to the main points for consideration when undertaking beach modelling. Fuller details are presented in Sections 4 to 10.

2.1 Common themes

Although many of the lessons learned are specific to certain models or stages in the modelling and design process, there are a number of common themes (Box 2.1).

In addition to the points listed in Box 2.1, there are two further important points to note when considering modelling.

- Models should be used to inform a design, not be relied on solely to provide the solution; modelling is just one part of the toolkit. Coastal engineering expertise and judgement, past performance and local knowledge all combine to form an important part of process that links modelling approaches and are crucial to the final design of a successful beach scheme.
- A designer or client will usually be looking for 'certainty' of outcome from the modelling, but this is not a realistic expectation. Models and other predictive techniques are essentially generalised, simplified representations of reality and as such the assumptions made in these methods mean that resulting predictions do have inherent limitations. Being aware of the assumptions made and limitations is necessary to be able to interpret results within confidence limits.

Several case studies suggest that a higher degree of certainty may be presented in the reporting of the modelling outcomes than should be provided. This leads to the mistaken belief that modelling can be looked at as providing definitive answers. But that is not what models do; rather they are a design tool to inform.

As a result, the design of schemes should include a large adaptive element that can accommodate design uncertainties as no beach scheme can be designed with ultimate certainty.

Box 2.1: Common themes from the comparative analysis

1. Often what is implemented is not what was modelled; for example, the recharge volumes or control structures are different. It is perhaps therefore inevitable that there are often differences between actual and predicted beach performance.

2. It is not uncommon for the actual beach nourishment material to be of a different size to that used in modelling. The grading of imported material is invariably wider than allowed for in modelling, usually with a higher fines content.

3. Conversely, beach models are not able to model wide graded material particularly well and therefore a degree of subjectivity must be employed.

4. A difference in wave climate is most commonly the fundamental difference between actual and predicted beach performance. Wave climates used in modelling are often not representative of those that occur following construction. Future wave conditions and storm sequences will always differ from measured or modelled historical wave climate data, but there is no doubt that the quality of input wave data has a major impact on the accuracy of beach modelling.

5. It is usual for a series of models to be used in combination to develop a beach scheme; rarely is a design based solely on one model type. As such, coastal engineering knowledge and the expertise to effectively understand and combine the outputs from these different tools is imperative.

6. Beach models are rarely validated or re-run to examine changes in performance and potential improvement to the beach management regime.

7. Information on how model outputs translate into the final design decisions, and then exactly what beach management activity has taken place, are generally very poorly recorded. Without improvement in this, it will continue to be difficult to make subsequent evaluation of the effectiveness of approaches and potential improvement to techniques for future benefit.

2.2 Overall approach to beach modelling

The overall approach to considering and undertaking modelling is set out in Figure 2.1, which also shows where to find details relating to each step.

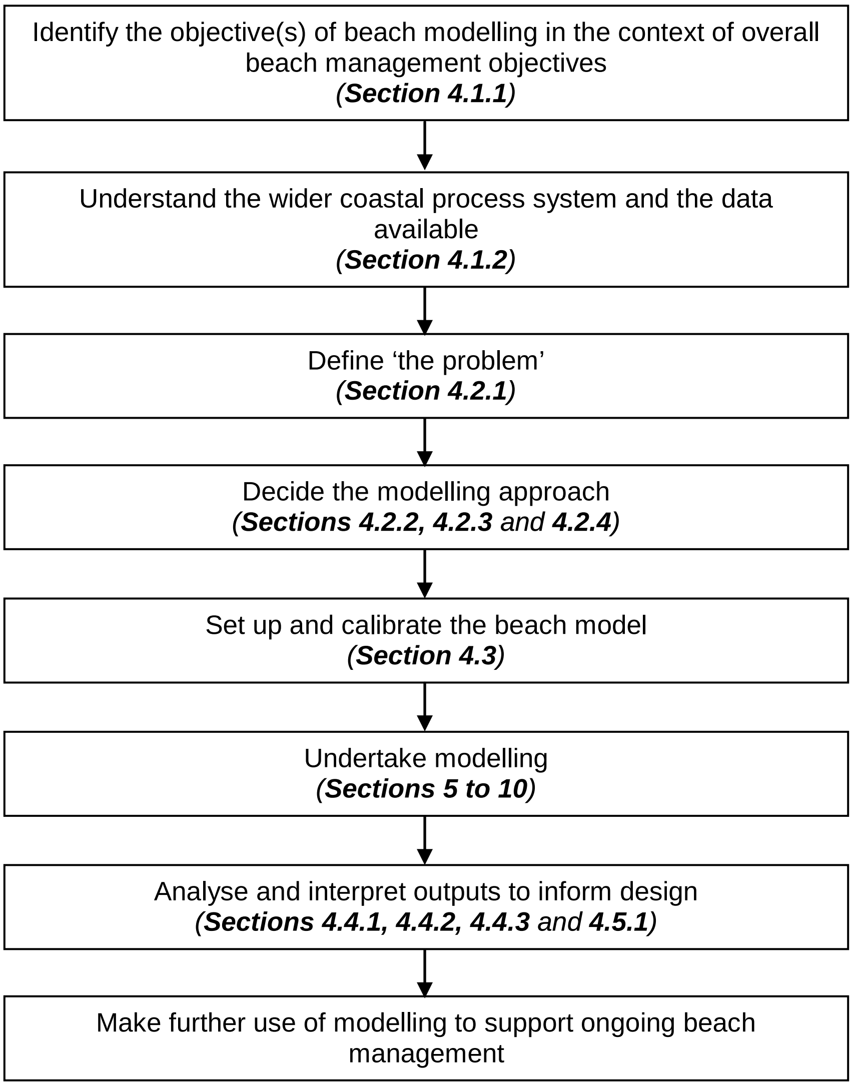

Figure 2.1 Flow chart on 'Approach to Beach Modelling'

Boxes 2.2 and 2.3 identify the crucial points to consider when planning and delivering the application of modelling approaches for beach design or management. More detail on all of these points can be found in Section 4.

Box 2.2: Key points on approach to beach modelling in scheme design and management

1. Define the problem that needs to be addressed before deciding on the approach to adopt. Be clear on what the actual objectives are and what that approach can provide.

2. Understand the site. Know the basic processes occurring at the site to appreciate the problems that the model needs to resolve.

3. Look wider than the scheme's defined boundaries. Consider the wider coastal system processes and other schemes on surrounding coastlines that might affect or can inform this scheme and account for these.

4. Establish the information available for setting up, running and calibrating the model or approach. The amount and quality of this information will influence the type of approach adopted and the uncertainty associated with the outputs.

5. Modelling is just part of the toolkit. The inherent limitations of models, or the data

Box 2.2: Key points on approach to beach modelling in scheme design and management

used in them, mean these alone provide only limited insight into the way the beach will behave in the future, not the complete picture. Local knowledge and coastal engineering experience are just as essential; it is the appropriate interpretation of the outputs that is critical.

6. Document the approach taken to modelling, including assumptions and rationale for that approach. Include uncertainties and gaps in knowledge so others in the future are well informed and can use the knowledge from the modelling appropriately. Summarise the approach in the Beach Management Plan for easy reference and transparency.

7. Sensitivity tests to assess the impacts of varying sediment grain sizes and wave climates should normally be used to inform the potential range of outcomes and thus provide a stronger design.

8. Scenario assessment can be an effective way of building an envelope of potential beach behaviours to provide a better informed response by the operational teams in future beach management of a site.

9. Updating models with new information as it becomes available can provide a cost-effective means to adapt the implementation of beach management (for example, Seaford, Hurst).

10. Document ongoing beach management activities and keep the Beach Management Plan up-to-date.

Box 2.3: Key points on setting up beach models

1. All models have limits on their applicability relating to various parameters. Models are often used outside these limitations, particularly with regard to sediment size. The implications of doing this need to be appreciated and stated.

2. Given the inherent model uncertainties, the quality of model outputs will generally reflect the quality of input data.

3. It is important to ensure that input variables are appropriately defined at the outset.

4. Models are not always calibrated, although the processes within many of them have been validated in their development. Calibration should wherever possible be undertaken with actual data to obtain reliable results for the site in question.

5. Calibration is not always possible due to lack of suitable information. In such instances, models need to be used pragmatically and the level of confidence that can be placed in the results needs to be clearly identified.

2.3 Specific modelling tools and techniques

The vital points to be considered when applying different modelling tools and techniques are listed below.

2.3.1 One-line numerical beach plan shape models

Beach plan shape has generally been defined by the application of one-line models used to predict alongshore changes in beach position using mathematical equations solved using numerical methods. The most important points on their use arising from this study are presented in Box 2.4, with more detail given in Section 5.

Box 2.4: Observations on the use of one-line beach plan shape models

1. May be used to predict medium- to long-term shoreline changes – outputs can be predicted shoreline positions at different time steps and/or longshore sediment transport rates.

2. Originally developed for straight sand beaches, some have been extended (by varying model coefficients) to model shingle beaches. Differences between modelled and actual transport rates can often be attributed to the use of sediment size coefficients, although variability of input conditions (particularly waves) can also have significant impact on this.

3. Where there is strong curvature of the shoreline or complex beach processes, the model may not be accurate or appropriate. A simplified version of the model may provide a better outcome than trying to replicate actual beach response precisely.

4. Drift rates are sensitive to wave height and direction. High quality definition of the wave climate is therefore important, with suitably long time-series to establish annual variability.

5. Understanding gross drift rates as well as net drift is vital where drift reversals are encountered. Failure to do this can lead to misinterpretation of results. One-line beach plan shape models can be a valuable tool to help provide this understanding.

2.3.2 Empirical beach plan shape methods

Empirical methods used to predict plan shape change include equilibrium plan shape methods and empirical rules for the outline configuration of structures and beach shape. Important points on their use arising from this study are presented in Box 2.5, with more detail given in Section 6.

Box 2.5: Observations on the use of empirical beach plan shape methods

1. Empirical plan shape methods are useful, quick and easy to apply, but do have limitations. For example they are generally based upon equilibrium shape and so do not include temporal changes.

2. Stable (equilibrium) bay shape methods have proved to be exceptionally reliable for predicting beach shape where there are strongly unidirectional waves.

3. Although empirical rules can be effective tools, they are also very simplistic and issues that can affect their reliability include assumptions on availability of material supply and sediment transport processes.

4. With empirical beach plan shape methods, structures are generally presumed to be solid barriers, that is, material cannot pass over or through them.

2.3.3 Cross-shore beach profile models

Cross-shore profile models are used to predict the changes to the shape of a beach profile in response to wave action and currents usually over a relatively short period of time, for example, during a storm event. Important points on their use arising from this study are presented in Box 2.6, with more detail provided in Section 7.

Box 2.6: Observations on the use of cross-shore beach profile models

1. These approaches are often relatively quick and easy to use.

2. The prediction of short-term response for single wave and water level conditions is useful for informing on extreme aspects of beach response (for example, during storms) and thus beach volume requirements to protect against large events.

3. These models are less useful for predicting longer term beach evolution because they are limited in accounting for rollback and beach building processes.

4. No models or empirical tests are presently available to accurately model mixed beach profile response. The profile response to these lower permeability beaches is different with higher reflections, cementation and cliffing, which present models do not replicate.

5. None of the presently available cross-shore profile models replicate beach response to bimodal wave conditions.

2.3.4 Physical models

Physical modelling can be conducted in either a two-dimensional (2D) wave flume or a three-dimensional (3D) wave basin. Modelling enables a scaled representation of some of the hydrodynamic processes, beach responses and structural influences. Important points on their use arising from this study are presented in Box 2.7, with more detail given in Section 8.

Box 2.7: Observations on the use of physical models

Wave basin physical models

1. A constraint of physical models for beach profile response is the scaling of smaller sized materials. Generally sand sized material cannot be scaled accurately. This also limits the ability to replicate mixed beaches; there are currently no established methods for scaling mixed sand and gravel sediments.

2. Although three-dimensional physical models can represent wave processes better than numerical models, they are not normally expected to provide precise results for sediment transport on sand beaches. However, they are much better than numerical models for establishing beach evolution in the proximity of structures such as groynes, and so are often used in conjunction with numerical models.

3. Physical models enable the likely actual behaviour of a beach to be observed directly, but are usually more costly to set up and run than numerical or empirical methods. This can limit the extent of test conditions or variations on a scheme.

4. There is limited scope to return to a model to re-examine other scenarios at a later date, as the model may have been decommissioned. Physical modelling is

Box 2.7: Observations on the use of physical models

therefore often carried out in conjunction with other methods towards the end of the design process once the list of possible alternatives has been reduced.

2.3.5 Beach monitoring data for beach design and maintenance

The use of monitoring data to inform beach design and maintenance involves the analysis of beach survey information to predict changes at a specific site. Important points on their use arising from this study are presented in Box 2.8, with more detail given in Section 9.

Box 2.8: Observations on the use of beach monitoring-based design

1. Monitoring provides an actual record of beach response, which models are attempting to produce, so a high degree of confidence can be placed in these designs. Where available, long-term beach monitoring datasets can be used to reliably indicate long-term trends of sediment drift, beach profile and plan shape changes.

2. However, this actual record is just a snapshot in time and may not be representative of all states of the beach between surveys. Usually these data are only available in time steps of annual or six-monthly records, so the approach tends to be more useful to look at longer term underlying shoreline response.

3. A limitation of this method is that is cannot predict future beach response if future management practices are likely to differ from those used currently or previously.

2.4 Wave climate for beach modelling

An appreciation of the wave climate and extreme conditions is essential to predict beach behaviour. Wave action and longshore currents are the fundamental drivers of alongshore sand and shingle beach processes, and the majority of models used in beach design are driven by waves. Important points on wave climate arising from this study are presented in Box 2.9, with more detail given in Section 10.

Box 2.9: Key points on wave climate for beach modelling

1. The choice of wave modelling approach needs to be appropriate to deliver the transformations required for the type of beach modelling being undertaken.

2. Insufficient record length raises potential for biased/unrepresentative conditions and thus beach response predictions. Longer duration sets (that is, >10–15 years) are more likely to include conditions that are representative of mean and extreme conditions and the previous variability at the site.

3. Sensitivity tests should be undertaken when only short record lengths are available. When long records are available, tests to examine more energetic and less energetic periods are valuable to give an indication of variability.

4. Calibration of synthetic wave data with measured wave data can make significant improvements to the accuracy of sediment transport modelling.

5. Beach plan shape models are strongly dependent on accurate representation of significant wave height and direction. Good definition of bathymetry is therefore

Box 2.9: Key points on wave climate for beach modelling

also critical.

6. Cross-shore processes such as run-up and breaching are linked closely with wave period. Wave models investigated within this study have shown the accuracy of wave period data to be inadequate. Validation of modelled wave periods should be provided by measurements where possible.

7. Wave conditions characterised by bimodal wave periods may result in higher wave run-up and a greater possibility of breaching than conventional modelling methods can currently deal with. The only systematic approach to this variable at present is site-specific physical modelling.

3 Comparative analysis sites

3.1 Description

The lessons identified are based on comparative review of actual and predicted beach performance from selected past schemes at the locations shown in Figure 3.1.

The schemes used as case studies were selected to reflect a range of different beach types, management approaches and modelling applications rather than seeking a geographical spread. Indeed the specific locations of these schemes are not important but have been included to provide context to the assessments.

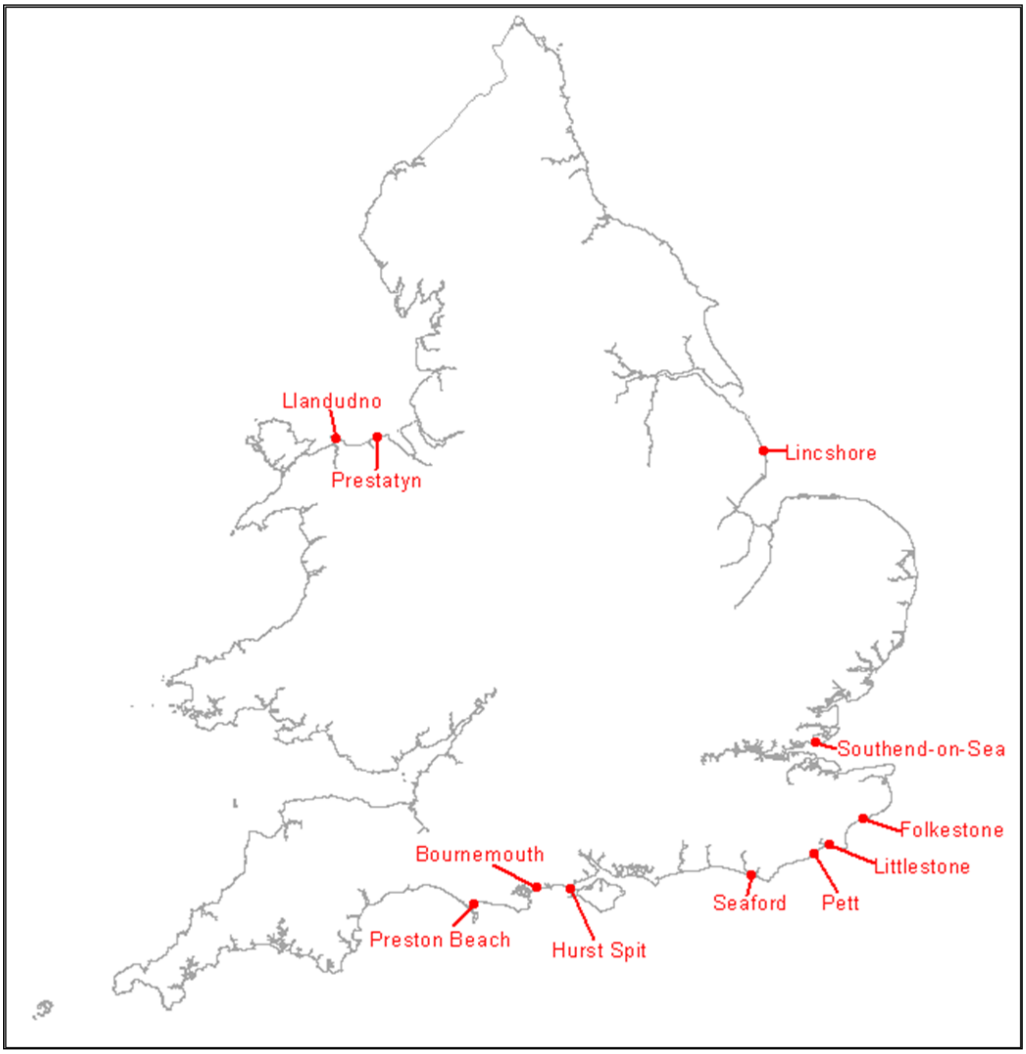

Figure 3.1 Location of the 11 sites selected for comparative analysis

3.2 Details

A brief introduction to each scheme, the main lessons and what sort of information might be found in the corresponding comparative analysis is given below. Important details relating to these lessons are presented in the Appendix, with fuller information on each scheme given in the separate technical report.

3.2.1 Bournemouth

This ongoing beach scheme was first implemented in 1974 and has been actively managed for almost 40 years without any recourse to modelling. There have been regular nourishments to maintain the beach to design levels, but those design levels and the requirements for recharge are all developed solely upon analysis and interpretation of beach survey data. This example illustrates how this information can be used in this way and the importance of maintaining comprehensive records of beach management activities and beach responses.

Figure 3.2 View of Bournemouth frontage (courtesy Alan Frampton)

Box 3.1: Bournemouth – main lessons for other schemes in the future

1. It is possible to manage a beach scheme over a long period of time without modelling, but this is only successful with knowledge built up over a considerable period of time, maintaining very comprehensive records, and ongoing expert interpretation of information.

2. It is impossible to say whether modelling of beach behaviour might have led to a more cost-effective or less effective scheme. However, limits on the ability to use past performance solely to predict future requirements will become increasingly difficult if accelerated climate change starts to alter the wave conditions from those experienced in the past.

3. Large-scale renourishments are more likely to experience higher losses, with these occurring early on in the life of the scheme. This needs to be accounted for when undertaking larger campaigns, though it has to be balanced against the potential disadvantages of more regular lower volume nourishment activities.

4. Constructing a beach to a lower than storm level and allowing nature to build the upper beach profile can help to avoid cliffing and improve public safety.

3.2.2 Folkestone

This scheme constructed in 2004 is an example of one developed through the application of established empirical plan shape design methods to create stable shingle embayments between artificial rock headlands. This example illustrates the high dependency of the success of the design on detailed wave modelling of the inshore wave climate, as is discussed at some length in this report.

Figure 3.3 Aerial view of Folkestone scheme post-construction (from CIRIA 2010)

Box 3.2: Folkestone – main lessons for other schemes in the future

1. The application of crenulate bay theory as an empirical model to design stable beaches can deliver a successful and sustainable solution that reflects naturally functioning shoreline features. Good definition of inshore wave direction is critical to that success.

2. If a similar approach is adopted elsewhere and the headland control structures are to be constructed from rock armour, then account should be taken of the transmission of wave energy over and through the structures which may affect the plan form locally.

3. The performance of the downdrift control points is susceptible to the structure form. Consequently care should be taken when deriving these points and when designing rock structures to act as control structures.

3.2.3 Hurst Spit

This scheme was constructed in 1996 to stabilise a shingle barrier beach, not backed by other structures, where management of its position and width/elevation are critical design factors. This example contains a comprehensive description of 3D physical modelling, used in conjunction with numerical modelling, to understand the processes and behavioural characteristics of the beach to provide an appropriate design. Particular detail is provided on the wave characteristics at the site and how these affect beach response and model predictions. Furthermore, this illustrates the use of monitoring in combination with understanding drawn from the extensive modelling to be able to confidently adapt the beach management regime.

Figure 3.4 View along Hurst Spit (courtesy New Forest District Council)

Box 3.3: Hurst Spit – main lessons for other schemes in the future

1. Design wave climates should include, as a minimum, several years of measured wave data to replace or complement numerical hindcasts. WAVEWATCH III appears to reproduce wave heights more reliably than past models, although some limitations remain.

2. Regularly occurring bimodal conditions may do more damage than extreme events determined using conventional extremes analysis methods. Assessments of wave climate need to examine the outputs of models and measured data carefully to determine whether bimodal conditions occur at the site.

3. Overwashing of the beach is underpredicted by the breach prediction model in bimodal wave conditions, but performs well when conditions lie within the limits of the original parametric framework.

4. A structured approach to monitoring and data analysis can provide a timely and detailed assessment of scheme performance to enable recalculation of the next interim recharge.

3.2.4 Lincshore (Mablethorpe to Skegness)

This is an example of a large-scale intensively managed open beach scheme. This sand recharge scheme covering over 20 km of frontage has been built up and maintained by annual renourishment campaigns for the past two decades (commenced in 1994 and ongoing). Wide-ranging detailed model studies were undertaken initially to understand coastal processes, develop the design and further evolve the scheme. The scheme now benefits from a comprehensive long term and highly detailed record of beach management activities and beach response, which forms the primary tool used for recent and future management decision-making.

Figure 3.5 Aerial view of recharge occurring along part of the Lincolnshire coast (from CIRIA 2010)

Box 3.4: Lincshore – main lessons for other schemes in the future

1. When uncalibrated models are used to derive long-term requirements for beach recharge, suitable contingency factors should either be included in deriving final estimates or the models should be revisited as better data become available.

2. Regular review of the performance and updating the beach management plan as new data become available is important, especially where beach response is highly volatile.

3. As longer term monitoring datasets become available they can provide a more reliable means to predict and plan future beach performance. Ahead of those data existing, comprehensive and wide ranging modelling can be critical for assessing and selecting the most appropriate beach management approach.

4. The objectives of all modelling exercises and how they relate to one another need to be clearly documented. Furthermore, the links between the model findings and subsequent design/implementation need to be explicitly documented.

3.2.5 Littlestone

This is an example of comprehensive modelling of an open shingle beach scheme, including plan shape and cross-shore, but where differences in actual environmental conditions from those expected and used to drive those models, compounded with a change in beach material size from that modelled, resulted in a quite different beach response. The scheme was constructed between 2002 and 2004.

Figure 3.6 Aerial view of Littlestone Beach (from Halcrow 2002)

Box 3.5: Littlestone – main lessons for other schemes in the future
1. For frontages that are potentially sensitive to changes in sediment transport direction, apply sensitivity tests to the directional wave data used in the model. This can provide an envelope of outcomes from which beach management options and the potential extent of variability/flexibility can be better determined. 2. When modelling sediment transport using a single sized value, recognise that most as-dredged material will be relatively wide-graded. This may result in a natural sorting of material with finer larger sediments being transported under different wave energy events. 3. The behaviour of mixed sand/shingle beaches is complex and not always well replicated by numerical sediment transport models. However, scenario testing considering a range of sediment sizes can help to better inform potential variability in the outcome. 4. There needs to be an element of engineering judgement applied to the results of the model. Validation of predictions is not always possible so reference to site inspections, monitoring data and local knowledge also needs to be considered.

3.2.6 Llandudno North Shore

This open beach scheme with phased works between 1996 and 2000 has a design supported by a range of different modelling approaches, including waves and sediment transport rates, followed by physical modelling to examine different configurations for the scheme. This example highlights the implications of changes between what was modelled and what is built, and the limitations of modelling only part of an interactive and interdependent coastal system.

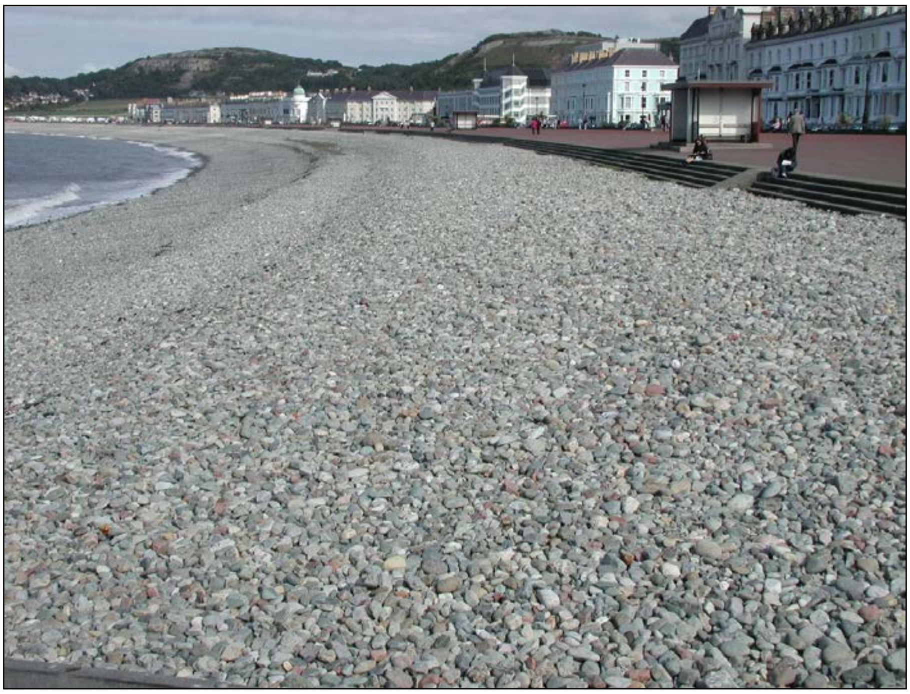

Figure 3.7 Llandudno Beach (courtesy Alan Williams)

Box 3.6: Llandudno – main lessons for other schemes in the future

1. Modelling should be considered as one of a range of tools to inform scheme definition for beach recharge schemes. A thorough understanding of process behaviour and likely scheme behaviour backed up by empirical calculation and judgement are essential.

2. It is importance to identifying appropriate boundary conditions for modelling and post scheme evaluation. Where appropriate, modelling may need to consider behaviour over a wider basis than just potential scheme limits.

3. Modelling should consider a range of potential sediment sizes.

4. As far as possible, modelling should seek to replicate potential future conditions or ranges of conditions against which actual scheme performance can be assessed.

5. Ideally modelling should provide sufficient information that can, in association with post-scheme monitoring, provide the basis for scheme performance evaluation and be used to inform future beach management requirements.

3.2.7 Pett (Cliff End to Rye Harbour)

This is an example of comprehensive one-dimensional (1D) modelling of alongshore shingle movement for an intensive recycling scheme along a groyned beach frontage that has been ongoing since 2004. Considerable detail is provided on the calibration and application of the plan shape model. Discussion is also provided on the use of cross-shore beach models used in combination with this to design the groyne lengths and spacing. This is also an example of where the management regime was not able to adhere to the planned programme of works, but information gained from modelling still proved useful to understand ongoing beach behaviour and to inform the management response.

Figure 3.8 View along part of the Pett frontage (courtesy Helen Jay)

Box 3.7: Pett – main lessons for other schemes in the future

1. The timing of scheme construction relative to completion of modelling studies can have an impact on the predicted behaviour of the scheme. Ensure that the most up-to-date information is incorporated prior to construction, with the impacts of any change fully considered.

2. Modelling of this coast led to a greater understanding of the processes and beach response. So although the scheme did not follow the proposed plan of works, the models provided a large amount of information to inform decisions on how to respond to changes in the scheme. This information should continue to be available to the coastal managers.

3. Modelling can indicate where the uncertainties lay and the potential impacts of these uncertainties on potential beach behaviour. This led to a more flexible scheme being developed, with an emphasis on monitoring, and allowed for monitoring to determine the need for additional structures at a later date. This type of flexible approach works well where there are a number of uncertainties to be accommodated.

4. Calibration of the model was most successful in adopting a smaller theoretical sediment size in the model than the actual material on the beach. Although this would be an issue on beaches replenished with dredged sediment, it can be acceptable where native sediment is the source of nourishment material.

5. Although there is debate about the suitability of one-line beach plan shape models for use on shingle beach, the application here appears to have been successful. This is most probably due to this that the beach model could actually be calibrated successfully.

3.2.8 Prestatyn

This scheme constructed in 1993 was designed based largely on local knowledge and experience without the use of numerical models (other than offshore wave climate). The design was for a one-off capital recharge on a beach stabilised with rock groynes.

Figure 3.9 Aerial view of Prestatyn Beach (from Halcrow 2002)

Box 3.8: Prestatyn – main lessons for other schemes in the future
1. In many aspects, specific local knowledge and experience can be equally important as detailed modelling, although a thorough understanding of process behaviour and likely scheme impacts backed up by empirical calculation and judgement are essential. 2. Detailed and in some cases expensive modelling may not always be necessary. However consideration of all available design tools, including modelling, is important at the outset to ensure the design is based on the best possible understanding.

3.2.9 Preston Beach (Weymouth)

This is an example of a scheme that was comprehensively modelled but has responded differently from expected in both alongshore and cross-shore directions. This was in part owing to its orientation relative to wave direction and differences in the wave climate, and the use of different sized and wider graded renourishment material. In this example an unusual but effective approach was taken to address the problem of cliffing of the beach resulting from the high fines content in the recharge material. The scheme was constructed in 1995-1996.

Figure 3.10 View southwards along Preston Beach (courtesy Alan Frampton)

Box 3.9: Preston Beach – main lessons for other schemes in the future
1. The available material should be ascertained prior to modelling where possible, so that the model reflects the final beach delivered. Ideally modelling should be delayed if appropriate field data are not available as incorrect assumptions can led to the need for remedial works and higher levels of ongoing maintenance. 2. Where drift is generally considered to be at a low rate, attention must be given to gross transport rates too, especially where very small changes in wave approach angles might result in different conclusions regarding direction and thus management of that beach. 3. Although sediment transport rates calculations may lie within the expected range of outputs from the models applied, it would be beneficial if any susceptibility to variability were clearly highlighted in reporting the results. 4. Sensitivity assessment would be helpful to identify the range of potential outputs. The range of sensitivity values to be tested could be guided by identification of the expected available sediment source/grading prior to modelling. 5. Returning to a beach to subsequently remove finer material to address permeability and performance issues is rare. But this might be an option to be considered in future with these costs compared against the costs of the likely levels of management activity from not doing so.

3.2.10 Seaford

This is an example of using both physical and numerical models when some of those approaches were in their infancy (the scheme was implemented in 1987) to design a scheme at a location with a long history of beach erosion and depletion, potentially compounded by previous activities. The site itself is a largely enclosed bay, with man-made controls to both east and west, but subject to variable longshore drift within that bay and with the potential to reach a stable equilibrium state prevented by a seawall protecting developed areas. This example shows the importance of identifying the right parameters and data for modelling and illustrates the appropriateness of identifying and stating known uncertainties in outputs at the time of design.

Figure 3.11 Seaford Beach (courtesy Worthing Borough Council)

Box 3.10: Seaford – main lessons for other schemes in the future

1. Although time series of wind data and measured wave data is the best available at the time of design, it is essential to recognise any limitations and caveat the design accordingly, considering sensitivity to potential future differences.

2. Where possible, measured wave data should be used in design to complement numerical hindcasts to assess systematic bias in modelled data and to validate those data once transformed inshore.

3. Where possible the bathymetry used for modelling transformations should be carefully scrutinised and validated against any measured data. This will restrict the possibility of wave directions being incorrectly represented by the modelling.

4. Differences between actual and modelled sediment transport rates can reflect a combination of differences in wave climate, sediment size and perhaps model calibration for grain size. Sensitivity assessment would be helpful to identify the range of uncertainty relating to these differences, which could then be accounted for in the decision-making and implementation process.

5. Comprehensive field observations as an integral part of calibrating and updating the modelling are valuable, particularly at complex sites.

3.2.11 Southend-on-Sea

This beach recharge scheme constructed in 2001-2002 is in an estuary with a coarse shingle beach sitting above sand at the back of a wide intertidal mudflat, resulting in different wave conditions and beach response than might be seen on the open coast. This is also an example of where the lack of data at the time of design to drive and calibrate models has resulted in some conservatism in the prediction of future maintenance, which has not proved to be necessary to the extent expected.

Figure 3.12 View along Southend frontage (courtesy Nigel Pontee)

Box 3.11: Southend – main lessons for other schemes in the future

1. A conservative approach can lead to the overestimation of costs, which could make a scheme appear less well economically justified than is actually the case.

2. Short term (for example, five years) wind and wave data to inform the design is not generally long enough to reliably derive the mean or the range of the expected annual wave climate. Although by chance the period of data used was reasonably representative, if relatively energetic, this may have led to high estimates of sediment transport and added to the conservative nature of the design.

3. Beach behaviour in an estuary environment can potentially be affected by locally generated and open sea wave activity. These need to be effectively combined to fully represent the environmental characteristics at the site in any modelling; otherwise unexpected beach behaviour may occur and need to be managed.

4. Wide intertidal flats will have a significant effect on wave energy and direction. Consequently, gravel beaches sitting behind these may be less affected by regular conditions and only susceptible to cross-shore or alongshore movement from infrequent storm events. This same threshold to mobility will also apply to the beach recovery, which means that the potential for natural recovery may be limited. Modelling/design should therefore also consider this possibility for informing the beach management planning.

4 Approach to beach modelling

4.1 Deciding on approach

4.1.1 Identifying the objective

Before considering any beach modelling, the scheme promoter should first decide what the ultimate objective of the exercise is and the questions that need to be answered. By defining and sharing that at the outset through engagement with the coastal engineer/modeller, the appropriateness of different approaches can be most effectively identified.

For example, with this understanding an experienced modeller may be able to set up models to simulate a variety of conditions to deliver outputs in a bespoke manner better suited to answering the client's needs. Similarly, a client with a better understanding of what the modelling can and cannot be expected to deliver may prefer to adopt a different approach, for example, application of lower cost simplified techniques upon which to base decisions.

Commissioning organisations are therefore expected to obtain greater benefit from specifying what questions they want answered, rather than specifically what modelling they expect.

4.1.2 Understanding the problem

Having established the understanding that needs to be gained, the choice of approach will also depend upon the issues to be overcome and the information available to do so (see, for example, van Waveren et al. 1999).

It is necessary to know the driving factors along the coast, and the key aspects and variables for data inputs, by establishing:

- the domain in which the problem belongs (longshore/cross-shore)
- the time and spatial scales in which the problem occurs
- which physical processes are important
- the combination and significance of variables

The information gathered in response to these questions will help determine the best approach to any modelling for a specific location.

The amount and quality of information available for setting up, running and calibrating the model or approach will also affect the suitability and therefore choice of approach (for example, Brampton and Southgate, 2001). Sufficient emphasis needs to be placed on ensuring that correct and sufficient data are available from the start to help advise what level of modelling, if at all, can be undertaken and the extent to which any deficiencies in that respect could invalidate the approach.

When assessing these points there are a number of factors to consider (Box 4.1).

Box 4.1: Factors influencing choice of modelling approach

- Beach morphology (straight, curved coast, enclosed bay)
- Sedimentology (grain size, grading)
- Wave climate (extremes, averages)
- Tidal range
- Tidal/wave induced currents
- Boundary conditions (sediment inputs and outputs)
- Ability to incorporate control structures (and how)
- Backshore features (for example, seawalls, dunes, cliffs, low-lying land)
- Geological features (for example, headlands, underlying strata)
- Outputs required (sediment transport rates, hot spots, plan shape development)
- Importance of long-term or short-term change (storm events, lifecycle management)
- Risks arising from the current situation/scenario
- Types of management options to be considered

4.1.3 Recognising limitations

There are inevitably uncertainties associated with using models and techniques to predict beach behaviour. (Box 4.2) It is important to recognise the relative significance of these and clearly communicate them to those utilising the model outputs.

Some uncertainties are quantifiable, some unquantifiable (Brampton and Southgate, 2001). Unquantifiable uncertainties can differ for each situation and timescale used, but it is important to try and reduce these sources of uncertainty as much as possible. Sources of quantifiable uncertainty relate to those for which calculations can be made about the spread of predictions of future coastal change.

Box 4.2: Factors influencing model accuracy

Given a set of input data, the accuracy of the model results and confidence in the model will depend on:

- processes represented and not represented in the model and their relative importance
- accuracy of the mathematical equations
- scale of the model
- availability and quality of the data, especially the data used for calibration
- numerical method and model set-up used
- appropriate geometric and parametric representation of the beaches and structures

Models are often run outside their range of validity without giving proper consideration to the potential implications of doing so. It is easy to stray out of the ‘boundaries’ of the model leading to the over- or under-design of beaches in the past (see, for example, the Preston Beach case study).

In some circumstances, models are just not good enough to represent reality due to limitations or simplifications in the underlying processes represented. Other techniques or combinations of models and approaches therefore need to be used. There is also a danger that newer generation, increasingly sophisticated, models may appear to reduce these uncertainties, while in reality increasing complexity may result in more inaccurate or misleading results than if a simpler method was used. Engineering judgement and local knowledge play a critical part in identifying this and determining solutions to overcome these, as illustrated by the Bournemouth and Prestatyn case studies.

Several of the case studies have highlighted differences in sediment type, volume, timing of management actions and structures between model and implementation. The most likely approach to construction and management may drive the modelling approach, but alternatives in relation to an adaptive approach should be considered early on in the process.

4.1.4 How to proceed?

There are a range of approaches available to use in beach design and beach maintenance planning. These approaches include a number of modelling tools and other techniques and fall into the following main categories:

- numerical models
- empirical methods
- physical models
- use of monitoring and historical data
- engineering judgement and combinations of tools

Sections 5 to 9 discuss specific modelling tools and techniques in more detail, including the strengths, weaknesses and decisions they can help to support.

Different approaches to use of these models can be applicable for different situations and will depend upon the assessments made (see sections 4.1.1 to 4.1.3). For example, it might be appropriate to start with simple models and techniques to help better understand potential beach behaviour before deciding whether to move onto more complex modelling. Alternatively, the complexity of a situation may be better understood by using certain models in a simplistic form to inform expert judgement rather than seeking to reproduce beach responses precisely (and which may not be possible).

Modelling always produces an approximation of beach responses and an important benefit therefore is the ability to provide relative assessments of alternative scenarios for different schemes rather than absolute outputs, as illustrated by the Hurst Spit and Seaford case studies.

Models and other predictive techniques are essentially generalised, simplified representations of reality, and as such the assumptions made in these methods mean that resulting predictions do have inherent limitations. They invariably have a valid range over which they are expected to function but will be applied outside of the theoretical range of application. Being aware of the assumptions made and limitations of the tools/techniques is necessary to be able to interpret and caveat certain results with confidence limits.

4.2 Setting up beach models

4.2.1 Input data quality

Models are generally very sensitive to the parameters used, and representative inputs are required to obtain representative outputs. It is therefore vital that input variables are appropriately defined at the outset including:

- grain size
- profiles
- contours
- waves
- water levels
- structure geometry

4.2.2 Boundary conditions

Unless the beach is a closed cell, sediment will move in and out of the scheme. This requires an understanding of influences from, and impacts on, neighbouring frontages and offshore. These can be natural processes or structures, and management activities. Beach modelling needs to recognises and account for these interactions in defining and interpreting model results. Figure 4.1 shows an example of the types of interactions that need to be considered.

In most cases in the UK, broader regional assessments can be found in Futurecoast (Halcrow 2002), shoreline management plans and strategies.

Box 4.3: Understanding wider coastal processes
Knowledge of how geological, climatic, oceanographic and anthropogenic factors affect coastal processes, sediment transport, erosion and accretion patterns, and coastal morphology is central to forming a wider understanding of the coastal system in question. Offshore features such as islands, sandbanks and other permanent or changing bathymetric features should also be included in the wider systems' understanding as they can alter the hydrodynamics locally and thus beach response. This will inform the appropriate choice of model or technique combinations to be used. Expert and local knowledge will inform this understanding and selection.

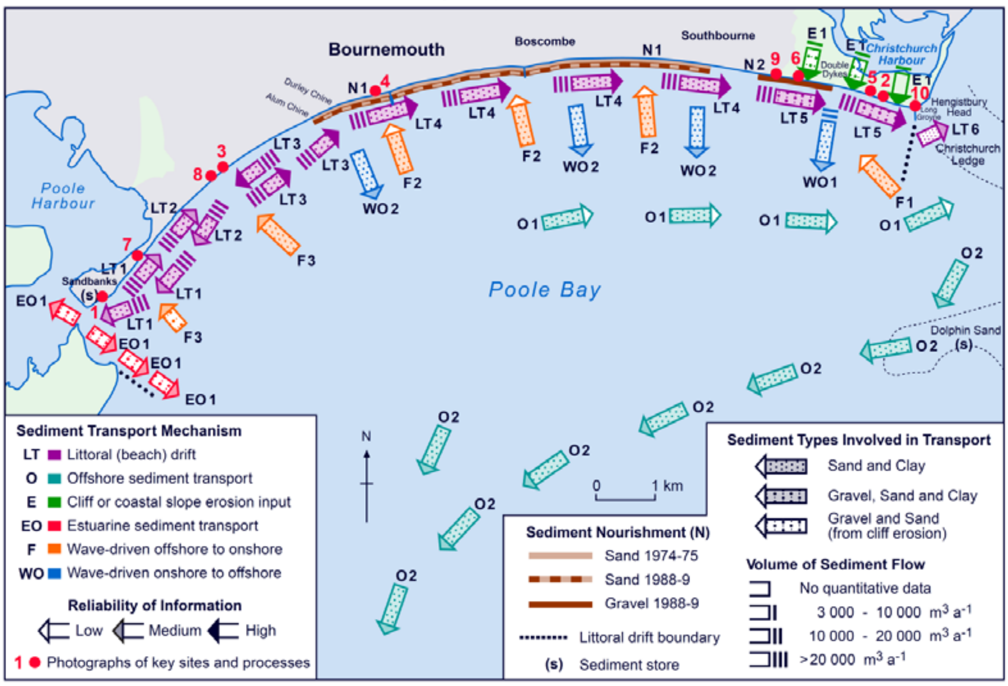

Figure 4.1 Example of conceptual understanding of wider processes affecting a shoreline (from Carter et al. 2004)

4.2.3 Beach material grading

All beach models have limits on their applicability relating the range of sediment sizes (that range generally being the upper and lower bounds of those sizes in the original tests from which the equations used in the model have been derived). There needs to be valid reasons to use a model outside of the range it is intended for; before doing so the appropriateness for sediment type and size should be determined. Figure 4.2 shows examples of sediment gradings.

Many numerical tools and empirical methods have been created based on the behaviour of sand beaches. In some cases, these models/techniques have been adapted by extrapolation for use on shingle or mixed beaches, but these have inherent limitations (see Box 4.4). Where models do allow for variability in sediment parameters across the spatial model domain, they may not allow for changes such as migration of coarse or finer sediment through the model.

Box 4.4: Potential limitations of models regarding beach material

Extrapolation of sand models for use on shingle or mixed beaches will have inherent limitations. For example these models may:

- assume that the beach sediment is uniform (for example, a single D_{50} value)
- assume uniformity in beach sediment cross-shore, alongshore and at depth
- ignore flows within the beach (for example, infiltration)
- assume that the threshold of motion is defined by the uniform particle size used
- assume full availability of sediment for transport and derive potential transport, erosion and accretion rather than actual
- take no account of sediment shape parameters

However, in the absence of better tools a pragmatic approach is often required. Using models outside their range of applicability can help to better understand a problem and provide direction on the solution. But rather than seeking precision of beach position, shape or volumes, they might usefully be applied to directly compare options or understand trends of beach behaviour. When models are run in this way outside of their valid limits, this needs to be highlighted with the potential implications fully understood. The Seaford and Preston Beach case studies demonstrate the more successful and less successful outcomes, respectively, that can arise from this approach.

Application of modelling tools with good quality on-site beach response data with which to calibrate them can also be a way of using models outside their theoretical limits with a reasonable degree of confidence. For example, where the originally derived formulae used in the model are adjusted to adapt the model for use on shingle beaches, the accuracy of predictions can be improved through calibrating the adjusted model with site-specific measured data. This is demonstrated in the Pett case study.

Predictions for mixed beaches are particularly limited due to increased complexity in their behaviour. Modelling for these beaches should therefore ideally be field data led or results at least calibrated or interpreted with reference to field data as far as possible. The Preston Beach case study illustrates the potential outcomes of not being able to calibrate models against field data.

Figure 4.2 Examples of different sediment gradings (courtesy Halcrow)

4.2.4 Model calibration

Calibration with actual data is needed to demonstrate a model provides a realistic representation of the beach. However, the purpose of many beach schemes is a fundamental change in the characteristics of the site through increasing the volume and geometry – often changing the grading of beach material – and/or introducing structures to control the behaviour of the beach.

Therefore calibration can only be carried out for the existing beach and reliance is placed on the fact that the processes within models have been validated using data from other sites or testing regimes. This is a limitation that needs to be recognised and appropriate caveats must be applied when interpreting results. Box 4.5 outlines some of the data that can help with model calibration and Figure 4.3 some example calibration results.

Box 4.5: Calibration data

Calibration data should ideally include a series of profile or grid surveys extending over a period of several years and covering the whole of the process unit to be modelled. It is particularly advantageous if short-term sediment transport rates can be assessed using the field data, within closed systems; sediment transport predictions are notoriously uncertain even under controlled conditions.

Attempts should be made to determine build-up rates of material against hard structures where possible.

Appropriate description of the grain size is required although it is notoriously difficult to achieve a representative beach grading.

Where data are to be used for one-line modelling, samples are best placed around the contour to be modelled.

Similarly, time series of wave data during the calibration period are extremely valuable; these might subsequently linked to the actual drift performance and plan shape evolution.

As beach plan shape modelling is very sensitive to minor changes in beach alignment and incident angle of wave attack, field data can provide a means of tuning the model

Box 4.5: Calibration data

to replicate previous changes.

The availability of data for calibration has often been an issue, particularly for schemes designed prior to the introduction of regular monitoring, such as Preston Beach. This situation has now improved considerably and suitably long datasets exist for many more locations ahead of schemes being developed in the future.

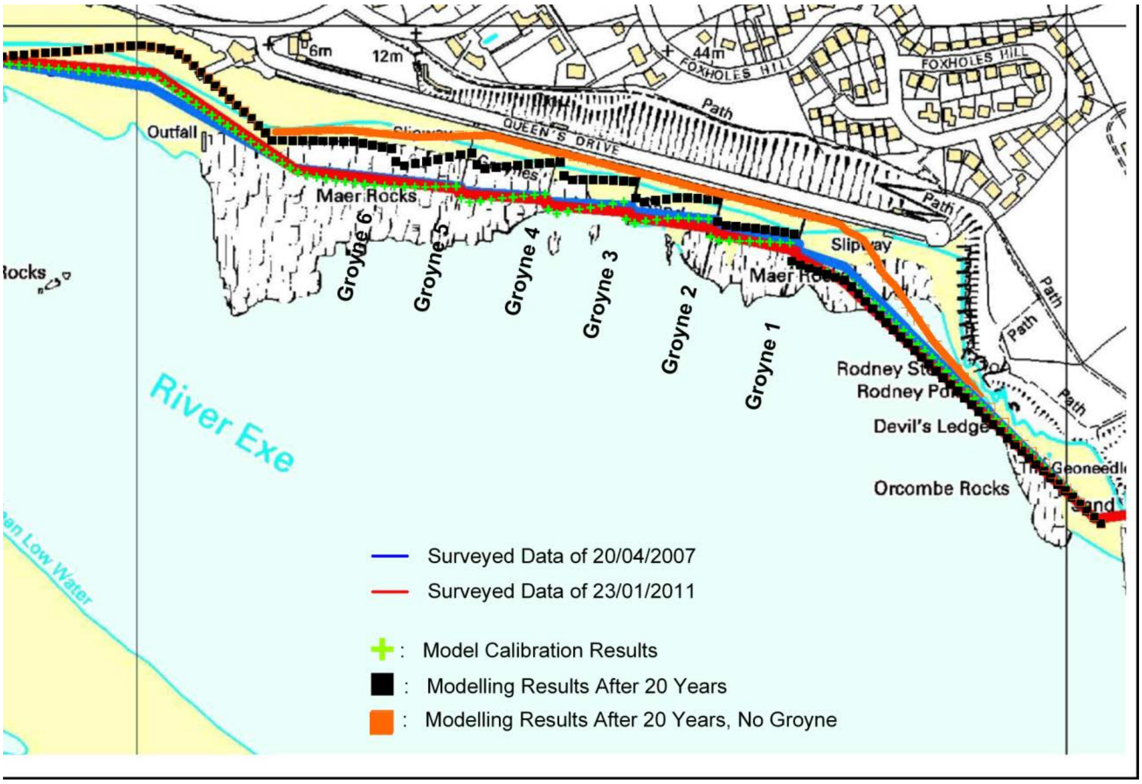

Figure 4.3 Example of one-line beach plan shape model calibration results (from Halcrow 2013)

4.2.5 Sensitivity testing to assess limitations

Sensitivity testing should be an integral part of the modelling process (Figure 4.4). The significance of assumptions and potential limitations regarding input variables (quality, record length) can be explored quantitatively and qualitatively , with the consequences of changes incorporated into technical and economic decision-making for selection of the preferred scheme (for example see the Seaford and Pett case studies).

Although there are many variables that can be assessed in sensitivity tests, each scheme and modelling exercise is unique and choices on which tests are required need to be informed by the modelling process itself. A checklist of those factors that can have most impact upon commonly used model outputs is provided in Box 4.6.

Box 4.6: Sensitivity testing checklist

- Wave direction (plan shape and cross-shore modelling)
- Wave height and period distribution (plan shape and cross-shore modelling)
- Sequence of wave conditions (plan shape and cross-shore modelling)
- Longshore variability of wave climate (plan shape modelling)
- Storm frequency and intensity (plan shape and cross-shore modelling)
- Sediment size (plan shape and cross-shore modelling)

Box 4.6: Sensitivity testing checklist

- Sediment grading (plan shape and cross-shore modelling)
- Initial beach geometry (plan shape and cross-shore modelling)
- Orientation of shoreline position (plan shape modelling)
- Bathymetric changes (all wave modelling).

Care should be exercised in using the outputs from sensitivity tests when conducting any like-for-like comparison of results. Changes in variable input factors may not only produce different rates of change but could also produce quite different behaviours. For example, beach position at a specific point in time may be the 'worst case' for the base case but the worst case with different variables, for example, sediment size, may occur at a different place or point in time. An example of such variability in an actual situation can be seen in the Littlestone case study in relation to wave direction.

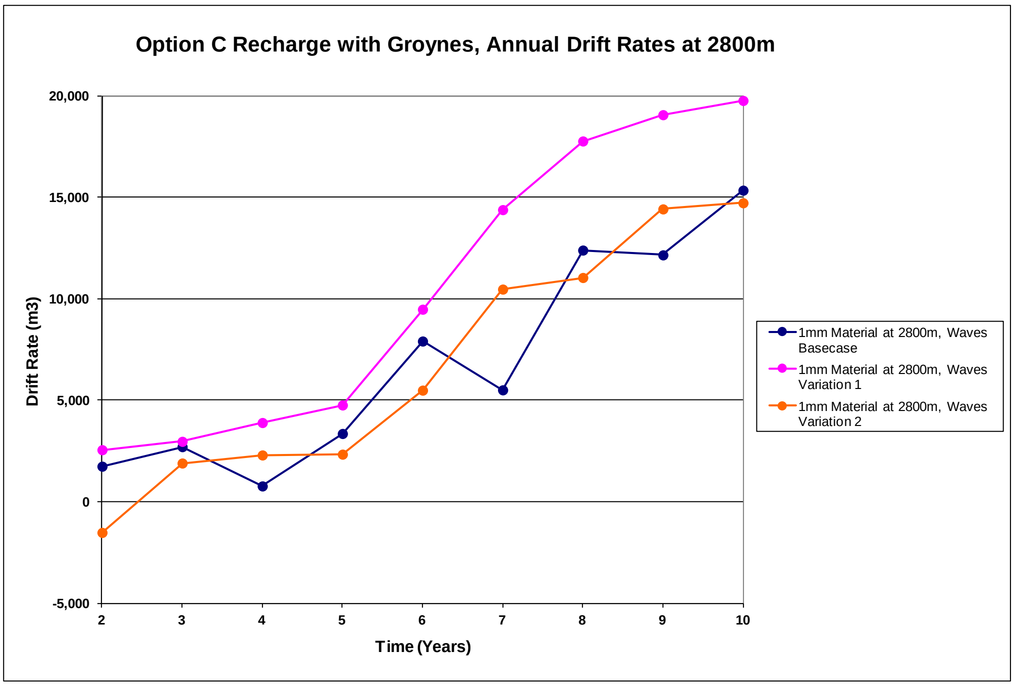

Figure 4.4 Example of sensitivity of one-line beach plan shape model calculated drift rates to variation in wave climate (refer to Appendix D of the supporting technical report)

4.3 Using model outputs

4.3.1 Interpreting results

Models are only one part of the design toolkit. Given the challenges to beach modelling described in sections 4.1 and 4.2, careful and critical interpretation of the results is required. Models can be an essential tool to be used by beach managers and coastal engineers to inform a design, but should not to be relied on solely to provide the solution. Coastal engineering expertise and judgement, past performance and local knowledge all combine to form an important part of process that links modelling approaches and are crucial to the final design of a successful beach scheme.

It is the appropriate interpretation of the modelling outputs that is important and suitable expertise should be applied to interpret the results and identify any potential anomalies or spurious results. A conceptual understanding of the processes and interactions combined with experience means a more realistic assessment of likely beach behaviour can be made and provided in those outputs where validation is not possible.

4.3.2 Adjusting the design

There may be a significant time lapse between the original modelling and actual scheme implementation, by which time some changes to the site may have occurred. Where there are now different conditions from what was modelled, it is inevitable that beach behaviour is likely to be different from that predicted. The Pett case study illustrates this point.

Where there are identifiable differences at the outset then consideration should to be given to re-assessing their implications while the models are still available and before implementation begins.

Review of the case studies indicates that models are rarely re-applied to assess those differences. Remodelling might have led to a modified and perhaps more cost effective scheme implementation. In future scheme development remodelling of known changes in variables that could affect the outcome ought to be considered.

Box 4.7: Updating the design

Known changes in variables that may warrant remodelling include:

- where it is known that the recharge material is different
- where the scheme phasing has been altered to deal with changes in implementation
- where the time that has elapsed means that bathy/beach conditions have altered
- where more data are available to inform the final scheme

The current national network of coastal monitoring programmes provides annual updates on the state of the beaches. The standard outputs from the programme enable an ‘at a glance’ assessment of coastal change, which can also be examined in detail to determine the need for any remodelling.

4.3.3 Revisiting the modelling/scenario assessment

Evidence from the case studies indicates that what is built, and when, is sometimes not what was modelled. Inevitably this can mean different outcomes in terms of actual beach performance compared with that expected, as illustrated by the Llandudno and Pett case studies.

The circumstances leading to this are often unforeseen at the time of modelling and design, and so not allowed for during that process. For example, anecdotal information suggests that fluctuations in prices or funding requirements can drive unplanned approaches to providing beach material or control structures. Similar situations may occur due to environmental constraints, for example, ‘grabbing’ material before it moves onto a designated area; the Littlestone case study demonstrates how material can be ‘lost’ from the scheme as a consequence of not doing this.

A conservative approach is sometimes adopted to compensate for lack of data or uncertainty, for example, a plan to place more material than might actually be required, as seen in the Southend case study. This might be appropriate to reduce risk but can result in overdesign, and potentially mean a scheme appears unviable economically.

In most instances where changes in circumstances occur, modifications are made to the maintenance programmes, for example, at Seaford and Preston Beach. But despite the potential benefits of doing so, there is little evidence of remodelling being considered. This appears to be rarely if ever done, with a variety of reasons cited including the difficulties in resurrecting previous models and the cost of remodelling. In making those decisions, it is important to consider the cost of remodelling compared with the operational costs of several years of potentially inappropriate beach management activity.

Another way to accommodate future variability is to model different scenarios at the time of design, when it is also likely to be most cost-effective to do so. Undertaking scenario assessments will provide an envelope of behavioural responses, from which any unforeseen changes can be better managed. The future beach manager is better informed on potential outcomes and so able to make appropriately well informed, and potentially the most cost-effective, decisions at that time.

Box 4.8: Potential scenario assessments

Scenarios that might be considered include:

- changes in nourishment material characteristics
- changes to timing and volume of nourishment placement regimes
- changes to recycling patterns including timing, location and volumes
- changes in arrangements of structures or their geometry
- different phasing, for example, structures being introduced/removed at different times
- in combination effects of differences in waves/storm conditions with changes in management

4.3.4 Continuous improvement of beach management

As part of the beach management process it could be beneficial to periodically re-run the model or technique used in the design of the scheme with monitoring data to periodically update the forecast and help inform future management and maintenance of the beach as part of a feedback loop.

Significantly, this can provide invaluable wider knowledge to improve models and modelling techniques for other schemes. Changes may, for example, be made to the valid range of empirical management tools, and these may be extended or improved with the additional data (Bradbury et al. 2010). This approach may also be valuable when wave conditions have been quite different to those tested, or where technical advances have been made in determining improved sediment size coefficients (for example, Brampton and Millard 1996).

This could be of collective national benefit through increasingly efficient use of the overall flood and coastal erosion risk management budget by reducing the gap between expectations and actual performance. It may also help to establish a more flexible funding approach to optimise expenditure over a cycle of a number of years across a wide portfolio of schemes.

Box 4.9: Model validation and updating for continuous beach management

Post-scheme construction field data can be used to validate models. Validation can be conducted following modelling by comparison of the modelled scenarios with what has actually happened. It may be beneficial to re-run plan shape models to replicate the actual conditions; examples of this approach have shown that, while the initial results may have resulted in different responses to those later observed in field data, this may be a reflection of the time series used in the modelling. Use of a representative wave climate will enable the model results to be much closer to the actual coastal evolution

Box 4.9: Model validation and updating for continuous beach management

(Brampton and Millard 1996).

Without validation it is not possible to assess with any degree of confidence whether predictions made are reasonable, and whether the scheme management can be effectively modified and improved. However, the general lack of availability of monitoring data has precluded this in the past.

4.4 Documenting what has been done

4.4.1 The modelling approach and decision-making process

In beach design it is usually necessary to understand both cross-shore and longshore dynamics. It can also be important to consider the long-term as well as the short-term 'event' based response of the beach. Therefore a combination of different models and/or techniques is often used.

The process of using a number of different techniques to inform beach design can be a disjointed process. So the manner in which the modelling has been undertaken and how information from one has been used to inform the other should be set out clearly in the modelling and design reports for future reference.

Modelling reports and design documents often don't include all the relevant information that is sometimes contained in less accessible calculation files or model input files. It may not be necessary to make all of that information readily available but key factors need to be presented. The template used for the full case studies in this project potentially offers the basis for recording those details.

The designer or client will usually be looking for 'certainty' of outcome from the modelling, but this is not a realistic expectation. However, assessment of many of the case studies suggests that a higher degree of certainty is presented in the reporting of the modelling outcomes than should be provided. In a few instances, the uncertainties relating to the variables are discussed, but this is rarely the case and is not satisfactory. Reporting and interpretation of modelling outcomes needs to be conveyed in a manner that enables a proper assessment of the risks and uncertainty to the most likely modelling outcomes.

Documenting and communicating the design assumptions, how the design has been developed and what model outputs have been used to inform decisions can prove vital for later reference to highlight limitations and uncertainties. This would convey the range of potential outcomes after implementation if necessary for further evolution of the beach management activities. This could be captured in the Beach Management Plan.

4.4.2 Management actions

The case studies demonstrate that documentation of beach management activities is generally inadequate. This issue has also been highlighted regularly within regional coastal monitoring programmes. Again, this information is invaluable for subsequently understanding beach behaviour and making well-informed decisions for ongoing and future management. When management data are not available, observations of coastal change from monitoring alone present a false impression of coastal evolution.

Information that should be recorded in association with beach management includes:

- dates, volumes and locations of material placement
- dates, locations and details of structure modification
- locations of borrow sites and volumes extracted for recycling

Ideally beach volumes associated with recharge and recycling activities should be identified using in and out surveys describing the location and extent of extraction or deposition. Where this is not possible, simple records of the activities may provide an adequate description. This can be achieved using plant equipped with global positioning system (GPS) tracers and load cells.

5 One-line numerical beach plan shape models

5.1 Overview

Definition of beach plan shape has predominantly been through the application of one-line models. These process-based models use mathematical equations solved with numerical methods to predict medium to long term alongshore changes in the plan shape of the shoreline (beach and nearshore) due to the spatial variation in alongshore drift, caused by variations in wave conditions, small changes in orientation or the presence of structures (CIRIA 2010).

Table 5.1 provides an overview of one-line plan shape models, including their applicability, inputs, outputs, assumptions, strengths and limitations. Figure 5.1 shows some example results.

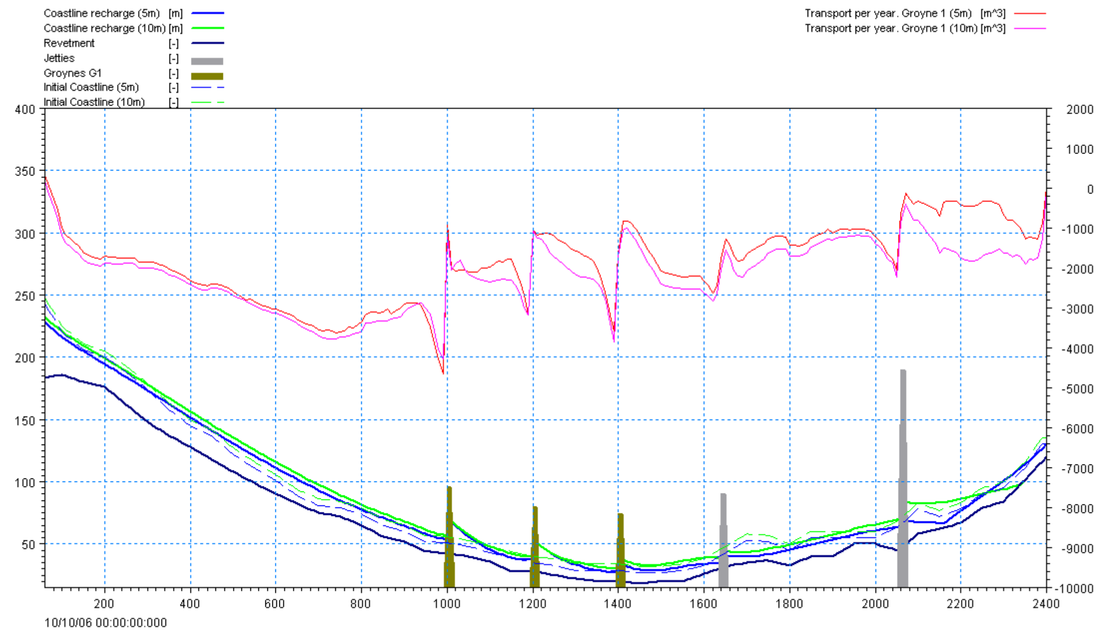

Figure 5.1 Example of one-line beach plan shape model results (from Halcrow 2010)

5.2 Observations on use

5.2.1 Considering whether to use the beach plan shape model

Appropriateness for the site

One-line beach plan shape models are the most mature of all beach plan models and so most confidence has been placed in their use. The original development of these models was based on simple field observations on long straight sandy beaches. Some of these models have since been extended to include coarser grain sizes primarily on an empirical trial and error basis. However, experienced users have noted that caution is still required in interpreting the results and that, while these models can be used to compare options, it is important to recognise their limitations.

Where there is strong curvature in the beach shape or strong diffraction effects from headlands, one-line numerical beach plan models may not be accurate. Where there are very wide tidal flats and shore normal waves, a one-line plan shape model may not be necessary. In some locations it may be that parts of the site can be represented well with a beach plan shape model but that this approach does not work well for other parts of the site. This was the case at Seaford, although this issue was highlighted in design tests and so accounted for.

In these circumstances or where the problem is complex, a simplified definition of the coast in the model may provide a better outcome than trying to precisely replicate actual beach response. This might feed into good expert interpretation and can be used to test assumptions and look at overall trends; for example see the Southend case study.

Appropriateness for the beach material type

Sediment transport formulae can differ from model to model so there is a need to ensure that the equations or factors used in the particular model are appropriate for the beach material type and size in question.

Equations have primarily been derived for sand beaches, with modified coefficients typically used to allow for application to coarser grain sizes. Sediment transport processes (described by the formulae) will differ on sand and shingle beaches, so any limitations related to grain size need to be identified and the potential range of variability should be investigated.

Some early applications of plan shape models to shingle beaches produced outputs that have subsequently been proven to underestimate the drift rates, see for example at Seaford where this resulted in subsequent modification of the scheme. This variability can often be attributed to the use of sediment size coefficients. Adaptation of these equations for shingle beaches has had limited success in the past without validation using site monitoring data (Axe et al. 1996, Brampton and Millard 1996).

Empirical calibrations using measured drift rates have enabled significant improvements in the reliability of this coefficient. This can be achieved at design stage by sensitivity testing with several sediment sizes. Post-construction monitoring has sometimes been used to review the performance of beaches relative to the model outputs. Remodelling of the beach with this calibration data can enable refinement of the model grain size/sediment transport coefficients for future management of the beach.

5.2.2 Setting up the beach plan shape model

Deciding which line(s) to model

In one-line beach plan shape models, the shoreline is represented by a single contour line and so it is necessary to decide the most appropriate contour to be modelled. Usually only one contour is examined, frequently mean sea level (MSL) or mean high water (MHW). This is acceptable for straightforward beaches and schemes, but where complex beach behaviour exists, it may be appropriate to investigate the sensitivity of results by modelling other beach contours too. An example might be where there are notable differences in the upper and lower beach materials. This may also allow influences on the model outputs, such as effectiveness of groynes, to be better understood, as one-line models are limited where a three-dimensional process predominates (that is, close to structures).

Defining sediment inputs

The way in which the model accounts for beach recharge should be understood. Different models may have different ways of dealing with this, for example, assuming it is a steady feed over a series of time steps or a single feed at a specific point in time. How the beach material is actually likely to be placed may also have an influence on the modelling output. A large recharge at a single location below the high water line would move the beach contour line further seaward into deeper water, potentially resulting in more rapid and even quite different dispersal of that material. If the processes in the model or the manner in which the model has been set up does not account for this then results could be inaccurate. Furthermore, differences between recharge regimes (for example, bi-annual or annual campaigns) may ultimately not be distinguishable from one another in the model outputs, potentially leading to inappropriate management decisions.

Defining wave conditions

Changes in beach morphology within one-line beach plan shape models are induced by waves breaking at an angle to the shoreline and consequent variations in the alongshore sediment transport rate. Drift rates at any given time and location will be sensitive to wave height, period and direction and these variables can vary on an hourly, daily, seasonal or annual basis. These models typically require waves to be supplied at a number of locations close to or just offshore from the closure depth; the models then internally transform the wave climate to the breaker line. Important considerations therefore include bathymetry, which will influence wave approach angle and breaking as well as the beach contour. The required spatial density of input wave conditions will vary according to the plan shape of the shoreline, exposure to wave conditions and the complexity of the bathymetry.

Wave time series may be represented in a number of ways. A morphological average condition derived from bulk statistics of the wave climate is a computationally efficient method, but much of the temporal variability of the beach response may be lost. More frequently, continuous time series of data are used to drive the model; a time series may range from daily conditions down to three-hourly records with modelling of at least a 10-year time series desirable. The benefit of this approach is that small inflexions in change are included in the modelling. Changes in drift direction can be identified more clearly with finer resolution time series; this can be particularly important at locations where net drift rates are low but gross drift rates are high. Breaking the time series down into smaller periods can provide valuable information on inter-annual variability. This can be achieved by either producing outputs at annual intervals or by running shorter sequences.

It is also important to consider the setting of the beach itself in relation to the tidal range. Usually models will account for varying water levels but, where this is not the case, allowance must be made for the beach contour probably experiencing wave action for only part of the tidal cycle. An example of this might be where a shingle beach is being modelled which sits on a sand foreshore above mean sea level.

Incorporating structures

The realistic representation of groynes or shore normal structures in plan shape models can be difficult. This is because one-line models have to work with an effective length that takes into account variations in the beach profile and make simple assumptions about the permeability and effective height of the groynes. Some models may use a cross-shore sediment transport distribution, but most only have a single bulk estimate of drift at each location and limited capability to represent bypassing. Efficiency factors are often used to represent factors such as permeability.

Representation of structure geometry is generally very simple. Models are often insufficiently sophisticated to be able to fully deal with complex structure shapes (for example, fishtail rock groynes), although detailed wave modelling can be used to take these into account in some circumstances. When models are used to optimise groyne lengths and spacing, careful interpretation of the model layout is required to develop the equivalent prototype layout.

Calibration

The application of many one-line beach plan shape models has been conducted without any calibration of the model. This can result in outcomes that do not accord with actual beach performance such as at Preston Beach where drift direction has been opposite to that predicted by modelling. Calibration (and validation) is required to improve confidence in the reliability of results.

Initial model setup may be based on a series of beach and bathymetric surveys that have been conducted prior to the modelling. Calibration involves making small changes to the model set-up or wave conditions to result in correct representation of the shoreline in the model. While this may appear to defeat the object of the modelling, the primary purpose of the initial stage of the modelling is often to test a range of alternative configurations of beaches and structures. It is important therefore to establish the reliability of the model for assessing present conditions. In this respect it may be useful to calibrate the model initially using a simplified plan layout of existing structures and beach.

The need for calibration can most significant at sites where frequent drift reversals may occur, resulting in a low net transport but high gross transport. For example in a low drift situation differences of just 1–2° in wave direction can result in quite different sediment transport results.

In the absence of detailed time series, beach profile survey data, historical mapping and aerial photographs should be explored as they may show changes to the nearby coast as a result of construction of breakwaters, harbours and so on that can be used for calibration.

5.2.3 Understanding outputs from beach plan shape modelling

Plan shape position

One-line beach plan shape models are frequently used to identify if and when a beach will achieve an equilibrium position – usually associated with beach recharge options. Achievement depends on both the wave climate and the geometry of the site. In many instances, structures such as seawalls prevent the beach from reaching an unconstrained equilibrium position. Under these circumstances, the plan shape may be used to assess a safe beach width and to identify the need for beach recycling or top-up of recharge. The beach management activity is optimised using the model outputs to plan timing, location and type of intervention.

It is useful to examine output beach position contours at different time steps. This may suggest a slowing rate of longshore transport and rate of change of the plan shape as the equilibrium shape is approached. It is valuable to assess these incremental steps in change, particularly when seeking to optimise the plan layout of alternative schemes. At Hurst Spit this approach identified changing plan shape and reduced drift by monitoring.

An initial assessment of the wave climate may also provide indications of general expectations from the modelling. Significant longshore variability of wave energy, for example, will affect the sediment transport rate and may result in rapid build-up in some areas or erosion in others.

Sediment transport rates

Another common use of the beach plan shape modelling is to determine the net sediment transport direction and to quantify the average annual rate of movement. In an ideal situation the output should include a description of variation arising from the time series of wave data. Models typically provide an incremental drift output based on a defined time interval, which usually provides a summary of gross drift quantities in both directions and the resultant net drift. This is valuable for the determination of drift reversals.

Understanding gross drift rates is vital where regular drift reversals are encountered. This is illustrated at Littlestone, where the drift direction post-construction has been in the opposite direction to that modelled pre-scheme and the control structures consequently less effective than predicted.

Many beaches experience high gross drift rates in both directions but low resultant net drift rate. For example, on a shingle beach calculations that suggest a net drift of 3,000 m^3 per year might be considered to be a low drift rate. It would valuable to conduct sensitivity tests to determine the effects of small (for example, 1^o) changes in direction of wave attack to the whole time series, or to look at subsets of the wave data to examine how this might affect the final outcomes of the modelling. While the designer will anticipate a correct output from the model, it is recommended that the uncertainty and sensitivity is also explained clearly with the results. Insufficient reporting of this can lead to the misinterpretation of outputs as small changes in wave climate, if not accounted for by the model, could lead to the risk of having incorrectly concluded the net drift direction altogether.

It is also possible for the finer material fraction of the beach to move in a different direction to the coarser material, or for a drift divide to be at different points on the beach for the different grain sizes. In some situations the wave climate also varies significantly along the shoreline. Under these circumstances it is reasonable to assume that the drift rates, and quite possibly directions, are likely to not adhere to a consistent pattern along the frontage. Features in the beach may become evident at locations where the drift rates speed up; these may be real features and these may be used to optimise location of structures.

In many situations the drift direction is consistently in a single direction and variations in the net drift can be a good indicator of beach change. However, quantification of the rates of transport is more challenging. Assessments suggest that drift rates derived by models that are better than a factor of two difference to the actual average rates are within the bounds of natural variability and can be considered to be performing acceptably. The Pett case study illustrates this point. General opinion is that this is generally a function of the variability of input conditions rather than a limitation of the model physics.

Table 5.1 Overview of one-line plan shape models

Description	To predict medium- to long-term shoreline changes due to the spatial variation in alongshore drift, caused by variations in wave conditions or the presence of structures
Applications	Primarily sand beaches, but also shingle and mixed beaches (providing calibration data available) Use where the plan shape/ maximum cut back of the beach is important to establish. To understand the impact of engineering works on the beach (seawalls, groynes, and to a lesser extent offshore breakwaters) Relatively straight coast Can be used in comparative applications to evaluate the performance of different schemes.
Temporal applicability	Months to tens of years (typically up to 30 years)
Spatial applicability	Hundreds of metres to several kilometres
Inputs	Initial contour line position (typically MSL or MHW) Beach profile or beach slope (depends on model formulation) Time series of wave and water levels, typically required at multiple nearshore locations along the coast, for example, from a wave transformation model. (Some models alternatively use a representative 'morphological' wave condition.) Height of active beach profile Sediment parameters – median particle size (D_{50}), grading parameters, porosity and density, depending on model formulation Coastal structures – type, location and geometry Boundary conditions – sediment inputs and outputs to / from the modelled area Data on past shoreline change for calibration
Computing requirements / calculations	Wave transformation calculations (included in some models, others rely on external model): • Refraction, shoaling and dissipation due to friction and wave breaking on a straight and parallel coast, and (sometimes) effect of diffraction by structures Flow calculations: • Only in some process based models. Not included in most models sediment transport is normally directly related to wave conditions. • Depth-averaged flows, can include effect of wave forcing and tides calculated along selected profiles. Sediment transport calculations: • Empirical or semi-empirical theories to predict longshore sediment transport rates. Some use a bulk littoral drift formula, others use detailed sediment transport theories. Shoreline change calculations: • Equation of conservation of sediment mass. The shoreline is divided into several sections. The movement of one contour line is calculated based on transport into and out of the section and

	the active beach height.
Outputs	Predicted shoreline positions at different time steps, typically can be specified by the user. Longshore sediment transport rate; for different time periods enabling calculation of gross and drift rates and variability as determined by the user
Assumptions	Assumes that the beach profile does not change.
Strengths	Predicts shoreline changes over engineering timescales. Once set up, models can be run quickly and economically for each year of wave input and for a range of design options. Can include user defined removal or addition of sediment to represent recycling and/or recharge.
General limitations	Calibration can be difficult. Not suitable for irregular-shaped shorelines or near estuary mouths Not generally applicable in areas of strong 2D circulations or strong tidal currents Diffraction and shore normal currents are not normally replicated. Assumes a fixed beach profile (which can vary along the model, but is not updated) for the duration of the simulation, which is not always correct in natural conditions, especially near structures. Does not include the effect of changes in beach profiles due to storms, hence used to consider annual or multi-annual change in position. Determining the effective length of shore normal breakwaters or groynes can be subjective. Some models can take into account linear shoreline protection limiting the erosion of the beach, but this can be problematic. Care needs to be taken modelling a renourished shoreline where the new profile or beach material is significantly different from the existing situation and thus assumptions made when calibrating the model. Models do not generally update far-field bathymetry (for example, not fully morphological). Do not include offshore movement of material unless defined externally as negative beach feed. Modelling oblique wave directions is problematic; one-line models become less useful as the wave angle increases.

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010), relevant studies (Environment Agency 2009, 2010a, 2011a, 2011b, 2011c) and user experience.

6 Empirical beach plan shape methods

6.1 Overview

Empirical methods are based on empirical observations in the field or laboratory, summarised into one or more predictive equations (CIRIA 2010). Empirical methods used to predict plan shape change can be divided into two categories:

- equilibrium plan shape methods
- empirical rules for the outline configuration of structures and beach shape

Although empirical methods used to predict plan shape change are quick and easy to apply, they do have considerable limitations. One of those is that the methods are generally based upon equilibrium shape and so do not include temporal changes. Nor do they cover many open coast beach situations adequately.

6.1.1 Equilibrium plan shape methods

Equilibrium plan shape methods typically use empirical equations based on logarithmic, parabolic and hyperbolic formulae to predict the equilibrium bay shape or analytical solutions to the one-line equation.

Table 6.1 provides an overview of equilibrium plan shape methods, including their applicability, inputs, outputs, assumptions, strengths and limitations.

6.1.2 Empirical rules

Empirical rules for the outline design of structures involve the use of design graphs that predict the shoreline response to beach control measures from field or model data. Examples include (Environment Agency 2010b):

- the beach positions resulting from the relationships between groyne spacing and length
- the relationships between reef length, spacing and offshore distance

Table 6.2 provides an overview of empirical rules for outline design of structures, including their applicability, inputs, outputs, assumptions, strengths and limitations.

6.2 Observations on use

6.2.1 Stable bay shape

Stable bay shape methods have proved to be exceptionally reliable in predicting beach behaviour where there are strongly unidirectional (or even distinct dual directional) waves and there is no or limited sediment transport interaction beyond the limits of the bay. A good example supporting this is seen in the Folkestone case study.

Factors that can lead to the successful design with this method include:

- good quality wave climate assessment to confirm the appropriateness of this approach and to produce the design beach plan shape
- accurate determination of the control points to correctly establish beach alignment and slope
- not underfilling the beach – the methods are generally for equilibrium plan forms so will only perform as expected if sufficient material exists
- placement to the theoretical planform, which can be advantageous to avoid unintended losses as the beach orientates itself
- careful consideration of structure shapes and storm beach profiles to avoid losses of beach material from the equilibrium bay

Figure 6.1 shows a definition sketch of stable way theory as proposed by Hsu and Evans (1989) and Silvester and Hsu (1997).

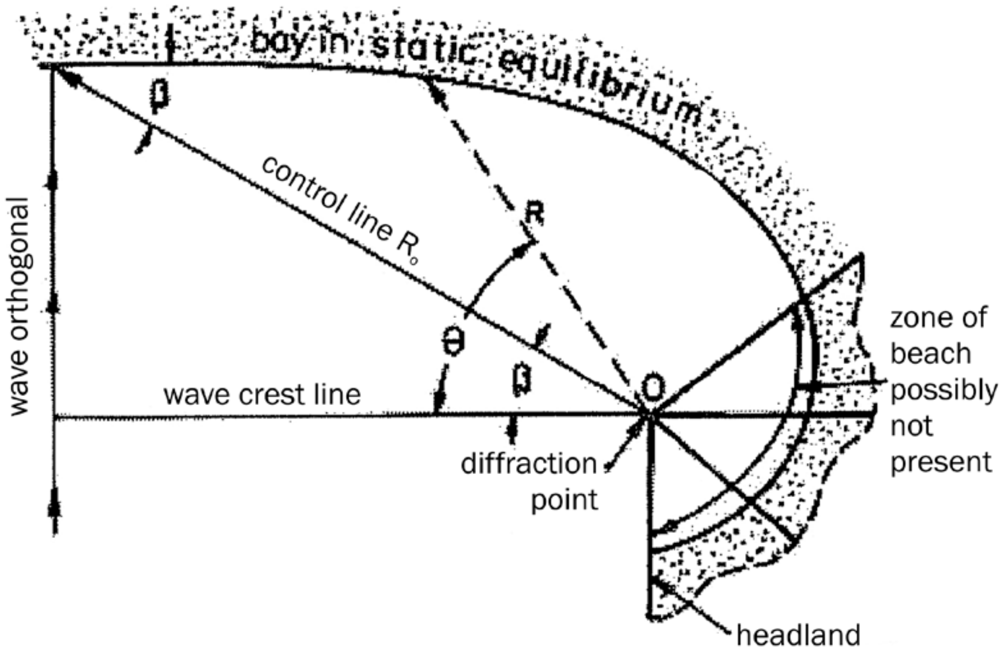

Figure 6.1 Stable bay theory (from CIRIA 2010)

6.2.2 Empirical rules for outline configuration of structures and beach shape

Although these can be effective tools, empirical methods are also very simplistic. Issues that can affect their reliability include:

- the availability of material (like equilibrium plan shape methods)
- the influence of alongshore or onshore–offshore sediment transport

In respect of the latter, not only might this be variable through time but also directly modify the overall plan shape that the beach actually takes.

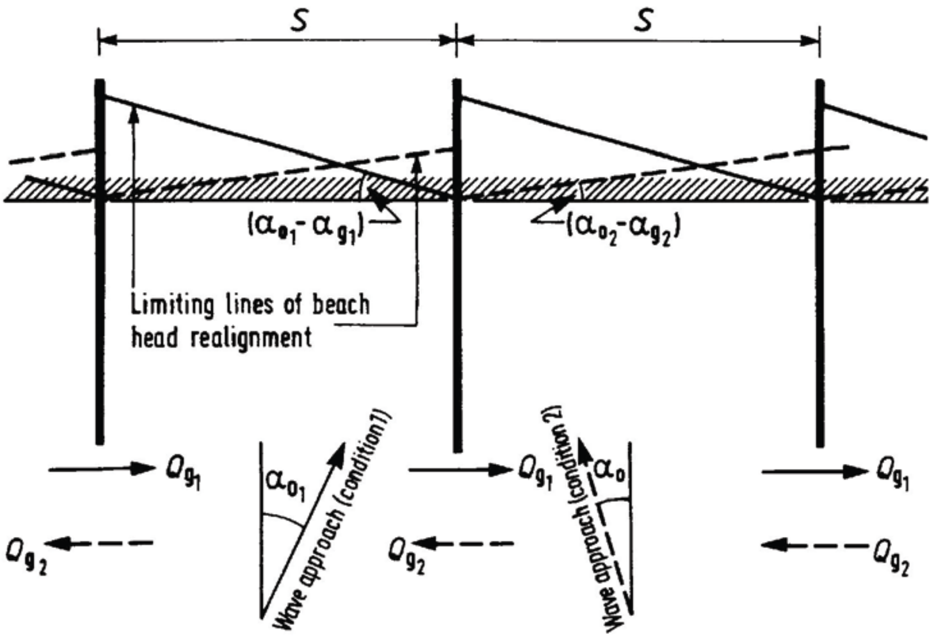

Figure 6.2 Variation of shoreline on a groyned beach (from Fleming 1990)

6.2.3 Considerations regarding structures

With empirical beach plan shape methods, structures are generally presumed to be solid barriers, that is, beach material will not go over them or through them. In reality both of these can occur, depending upon the nature of the structure (for example, rock or timber) and the elevation of the structure. This needs to be recognised when applying the techniques or specifying the structural design. It is also prudent to anticipate any need for potential amendments to the structures to 'tune' and improve them and to specify this in the Beach Management Plan.

Table 6.1 Overview of equilibrium plan shape methods

Description	Prediction of equilibrium bay shape using empirical relationships based on logarithmic, parabolic and hyperbolic formulae, including (but not exhaustively): • analytical solutions to one-line continuity equation – for example, Pelnard-Considere (1956). • parabolic shape equation (PBSE) of Hsu and Evans (1989) – links the change of shoreline to the point of diffraction, which is a fixed point that physically exists (either a natural headland or a coastal structure) • Silvester and Hsu (1997) – used to design artificial headlands • Spataru (1990) – simple method for calculating the equilibrium planshape of a beach behind detached breakwaters • salients behind breakwaters (USA)
Applications	Sand or shingle beaches (including large cobbles) To determine the shoreline plan form resulting from the influence of natural or artificial features such as headlands and large breakwaters Where there are dominant wave direction(s) at the beach Indented coastlines where wave conditions are influenced by the

	geometry of the entrance to the bay.
Temporal applicability	Long term (equilibrium shape)
Spatial applicability	Tens of metres to kilometres
Inputs	Bay geometry Predominant wave direction(s)
Computing requirements / calculations	Empirical equations used in this method include logarithmic spiral, parabolic and hyperbolic formulae, based on analysis of shoreline plan shapes from equilibrium bays. Equations can be easily coded to enable refinement and ease of analysis.
Outputs	Predicted beach shape between two points
Assumptions	Wave direction(s) remain constant and is not multi-directional. Sufficient volume of material exists to match beach shape. Typically, that the beach is self-contained (no material input/output).
Strengths	Easy and inexpensive to apply Theory proved in nature and simple to understand/be accepted.
General limitations	Up-coast and down-coast control points need to be established accurately, and at different states of the tide. Theoretical outputs may not describe the shape for the entire bay (some localised up-coast and down-coast variation can exist in reality). Uncertainty for tidal situations over which contour of the beach the shape defines (MLW, MSL, MHW, other?). Does not establish how long it will take for the equilibrium form to be reached or sediment transport rates. Wave conditions do vary so there can be temporal variations in the shape of the beach. May be unstable if used for a variable climate. Ideally the approach needs to be tailored to specific beaches.

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010) relevant studies (Environment Agency, 2009, 2010a, 2011a, 2011b, 2011c, and Brampton and Southgate 2001) and user experience.

Table 6.2 Overview of empirical rules for outline configuration of structures and beach shape

Description	Design graphs and empirical rules for predicting shoreline response of proposed beach control measures, including (but not exhaustively): • methods for designing groyne fields on sand and shingle beaches (for example, Fleming 1990) • US Army Corps of Engineers (USACE) Coastal Engineering Manual, Part V, Chapter 3 (USACE 2002) • empirical methods for outline design of beach control breakwaters on macro-tidal coasts (Environment Agency 2010b)
Applications	Sand and shingle beaches Determining geometry and configuration of structures

	(groynes/breakwaters) to provide a particular beach shape Establishing the plan shape of a beach in response to a particular configuration of structures (groynes/breakwaters) Empirical methods are often also used for outline design and scheme designs that are also progressed through numerical and sometimes physical modelling.
Temporal Applicability	Medium to long term
Spatial Applicability	Tens to hundreds of metres
Inputs	Wave direction for typical conditions and/or range of nearshore wave directions for storms. Beach extent required or structure geometry and configuration (one will be calculated based upon the other)
Computing requirements / calculations	Determine predominant wave conditions and desired beach extent then use design rules to assess the best possible configuration of structures. Determine predominant wave conditions and structural configuration then use design rules to establish beach shape. Rules can sometimes be coded
Outputs	Beach plan shape or structure arrangement (one will be calculated based upon the other)
Assumptions	Net sediment transport remains in balance (inputs and outputs are equal)
Strengths	They are simple to apply. Only involve a limited number of calculations. Can apply to coasts where there is a throughput of sediment (unlike equilibrium bay theory). To achieve design optimisation, this method could be used in conjunction with numerical or physical modelling.
General limitations	Does not recognise timescale, sediment type or geological constraints. Interpretation of rules and dimensional parameters such as effective groyne length are difficult in situations dominated by a tidal current.

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010) and user experience.

7 Cross-shore beach profile models and techniques

7.1 Overview

Cross-shore profile models are used to predict the changes to the shape of a beach profile in response to wave action and currents usually over a relatively short period of time (for example, during a storm event).

Both numerical and empirical methods exist covering sand and shingle beaches. The primary output from cross-shore models is a representation of the beach profile, although numerical models can also calculate cross-shore and longshore sediment transport rates across the profile.

7.1.1 Empirical methods

Equilibrium and parametric beach profile methods use relatively simple and easy to apply equations to predict the profile that a given beach will form under constant wave and water level conditions.

Table 7.1 provides an overview of empirical beach profile methods, including their applicability, inputs, outputs, assumptions, strengths and limitations. Figure 7.1 shows an example model output.

7.1.2 Numerical models

Process-based numerical models calculate changes in the beach using mathematical equations solved with numerical methods (CIRIA 2010). These normally predict the changes to the shape of a beach profile in response to varying wave action, currents and water levels.

Some 'numerical' models are little more than a rapid calculation tool for equilibrium theories and should really be regarded as empirical methods. The more sophisticated beach profile numerical models have primarily been developed for predicting changes on finer grained foreshores (sand and clay) where the processes are complex (see, for example, the Lincshore case study).

Table 7.2 provides an overview of beach profile models, including their applicability, inputs, outputs, assumptions, strengths and limitations.

No review of numerical cross-shore beach profile modelling was carried out within the case study comparative analysis and so observations on these methods are limited.

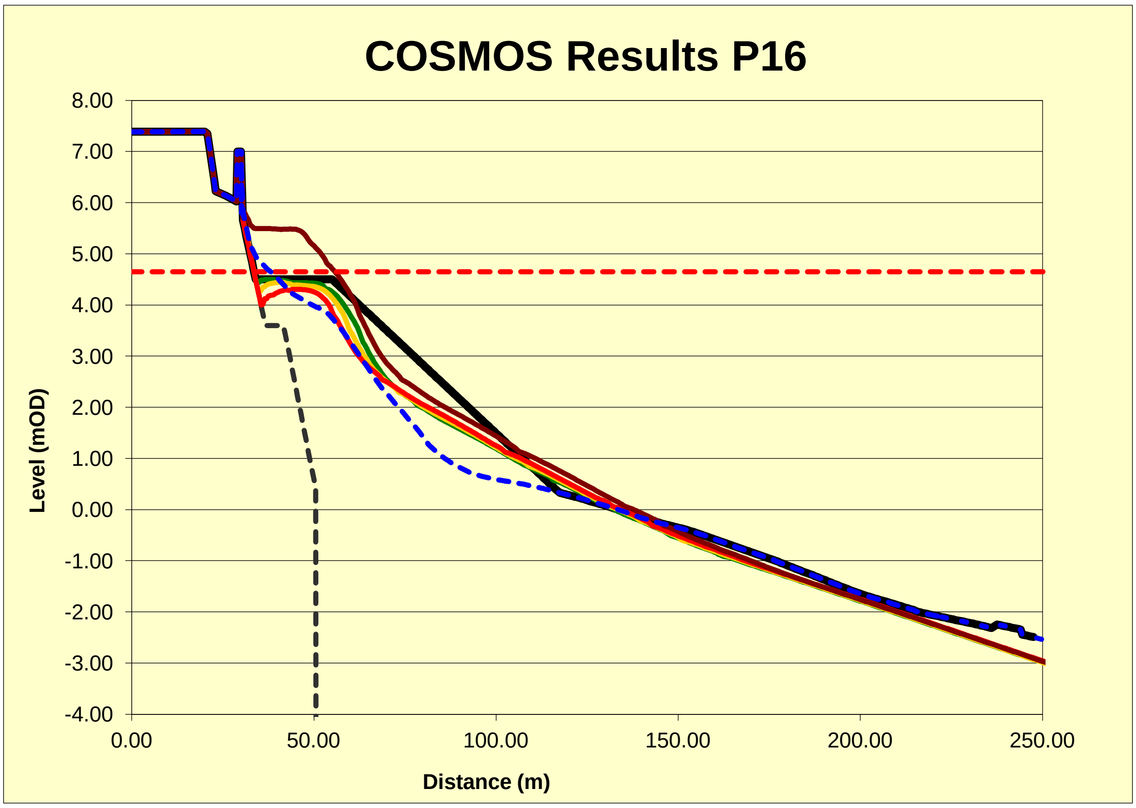

Figure 7.1 Example of cross-shore model output (courtesy Halcrow)

7.2 Observations on use

7.2.1 Setting up cross-shore models

Beach profile

An initial beach profile is set up in the models, usually based on surveyed data. However, there is an implicit assumption with using these models that the profile tested is representative of the actual beach just prior to the storm event. When the objective of the modelling is to assess the future risk of breaching or cross-shore erosion, the beach should be modelled for various stages in its anticipated lifecycle.

Validation of these models can be difficult as they generally provide only short-term response to storm conditions and actual beach profile data during storms are difficult to collect.

Beach material grading

Permeability of the beach is more influential than sediment size in cross-shore beach response, which makes modelling wide graded beaches of mixed composition difficult. The high fines proportion can lead to lower porosity, reflection, cementation and cliffing of the beach. The problem is that specific tools for cross-shore assessments do not currently exist for mixed sand and shingle beach gradings.

The approach often adopted at design is to represent the mixed beach grain size simply with a shingle-sized sediment grading and to use the empirical or process models originally developed for modelling shingle beaches (for example, Hurst Spit, Seaford and Preston Beach). This is not strictly valid as the erosion calculated by the cross-shore shingle model could be a significant underestimate when applied to mixed beaches. Large-scale model tests (Blanco et al*.* 2006) suggest that the profile response of pure shingle beaches results in a steeper beach with a higher crest than mixed beaches, where the crest is also likely to be set back further relative to still water level. Unfortunately there are not at present any empirical tests that develop these observations further. Figure 7.2 shows an example of beach cliffing.

Monitoring is therefore especially important for observing the cross-shore behaviour on mixed beaches and adjusting management assumptions accordingly.

Figure 7.2 Beach cliffing (from CIRIA 2010)

7.2.2 Use of empirical methods

Outputs typically represent a single situation (that is, one wave condition for one water level), whereas the beach will have experienced a range of waves over a varying tide. The outputs are therefore most appropriately used to inform on extreme aspects of beach response from which good estimations can usually be made of overall beach volume requirements. This might, for example, include how the beach crest might develop at the highest water levels, or how the lower beach might be drawn down. As such, a number of wave and water level conditions might be tested to develop a fuller understanding of overall beach response (as illustrated by the Hurst Spit case study).

A limitation of empirical cross-shore models is the lack of ability to replicate the beach building process, that is, the subsequent onshore movement of material drawn down under storm conditions. This is not generally a problem because their use is more commonly to look at design threshold conditions when beach drawdown is the issue.

Where wave run-up, overtopping and breaching is being investigated through use of these models, consideration should also be given to validation of the input wave period data. It has been demonstrated (Bradbury et al. 2006b) that some numerical wave models overestimate the wave period by about 20%.

None of the empirical cross-shore profile models replicate beach response to bimodal wave conditions. The significance of this is that these models may underestimate the vulnerability of these sites to breach or cross-shore erosion under such conditions (see the Hurst Spit case study for example).

Table 7.1 Overview of empirical beach profile methods

Description	Include both equilibrium and parametric beach profile empirical equations to predict the profile that a given beach will form under constant wave and water level conditions over a long period of time. These include (but not exhaustively): • Bruun Rule • Vellinga (1984) parametric beach profile equation • Dean (1997) equilibrium profile equation (sand) – used where there is a small tidal range • parametric method for shingle beaches (Powell 1990) – to assess shingle beach response (The method was developed for shingle beaches from physical modelling flume tests.) • Bradbury barrier breaching model (Bradbury et al. 2006a) – an empirical framework to predict the threshold for breaching of shingle barrier beaches, based on extensive fieldwork (at Hurst Spit) and physical model data
Applications	Shingle and sand beaches Predict the equilibrium beach profile in response to wave action. Assess changes in response to sea level rise. Investigate shingle beach response to assess beach recharge requirements. Barrier breaching equation is used to investigate shingle barrier inertia. Determination of closure depth
Temporal applicability	Short-term storm response and long-term average profile
Spatial applicability	Single location(s) along a beach
Inputs	Varies with method, but usually includes: • initial beach profile • water levels • wave conditions at the toe of the profile • sediment size
Computing requirements / calculations	Simple calculation Rules can be coded.
Outputs	Shape of beach profile
Assumptions	Assumes constant wave conditions. Assumes single sediment size.
Strengths	Simple to apply and only involve a limited number of calculations Most reliable where small tidal range
General limitations	Takes no account of geology or processes at the actual site. Assumed constant conditions do not occur in reality. Some equations have limitations, for example, may be only really

	valid for normal incident waves or specific material sizes/sediment distributions.

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010) relevant studies (Environment Agency, 2009, 2010a, 2011a, 2011b, 2011c) and user experience.

Table 7.2 Overview of beach profile numerical models

Description	Beach profile models model physical processes (waves, flow and sediment transport) to predict beach profile changes and cross-shore sediment transport (that is, offshore and onshore movement of sediment and the related change in profile shape). Some models also predict the cross-shore variation in alongshore sediment transport rates.
Applications	Used to; • determine expected beach erosion during extreme storm events along a straight open coast frontage • investigate response of a recharged beach • investigate beach response to wave reflection by a seawall • investigate changes in wave climate on the beach profile Primarily for sand beaches (and layered beaches, for example, sand above clay) Although some models are in development for shingle beaches and mixed beaches, these are not yet in general engineering use.
Temporal applicability	Short timescales: hours to days (response to specific storm events)
Spatial applicability	Single locations although often several sections considered in conjunction with one another
Inputs	Initial beach profile (and profile of substrata where relevant) Water levels Wave conditions at the toe of the profile Sediment parameters, typically size grading, grain density, porosity Other factors relating to cohesive sediment properties may be required.
Computing requirements / calculations	Wave transformation calculations: • Refraction, shoaling and dissipation due to friction and wave breaking Flow calculations: • Effect of wave forcing, wave asymmetry and vertical variation in the flow velocities across the profile Sediment transport calculations: • Empirical or semi-empirical theories to predict sediment transport rates across the profile Bed level change calculations: • Equation of conservation of sediment mass
Outputs	Shape of beach profile Sediment transport across and along profiles
Assumptions	Assumes that beach contours are straight and parallel (that is, the

	beach profile is uniform alongshore) unless several profiles analysed. Alongshore, wave conditions are assumed to be uniform (unless several profiles analysed and each defined separately).
Strengths	Some models can include revetments or non-erodible areas in the profile. Some models can be used to look at sub-beach down cutting, for example, clay beneath sand.
General limitations	Limited or no inclusion of alongshore effects, such as alongshore sediment transport or alongshore morphology changes If the model is run longer than a period of hours to days, model results are likely to become spurious. Generally unable to simulate accretion on the upper beach following storms as they are poor at modelling net onshore sediment transport. Unable to simulate overwash/ breaching scenarios. Calibration is more difficult than plan shape models due to limited site data on actual storm response – therefore should include sensitivity testing. Restricted to relatively short simulations of cross-shore transport. Can be limitations when used for a beach fronting a seawall.

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010) relevant studies (Environment Agency, 2009, 2010a, 2011a, 2011b, 2011c) and user experience.

8 Physical models

8.1 Overview

Physical modelling can be conducted in either a three-dimensional wave basin or a two-dimensional wave flume. Modelling enables a scaled representation of some of the hydrodynamic processes, beach responses and structural influences. Physical models of beach and structure systems are generally conducted with scaled mobile bed sediments. Beach profile physical modelling uses a wave flume to simulate beach profile change; where plan shape change also needs to be examined then a wave basin is used to simulate this.

Tables 8.1 and 8.2 provide an overview of wave basin and wave flume physical models, respectively, including their applicability, inputs, outputs, assumptions, strengths and limitations. Figure 8.1 shows an example set-up.

Figure 8.1 Physical model set-up (from CIRIA 2010)

8.2 Observations on use

8.2.1 Deciding whether and how to use a physical model

Physical models enable the likely actual behaviour of the beach to be observed directly, but are usually more costly to set up and run than either numerical or empirical methods. For those reasons, the number of test conditions or options may also be much more limited. Tests are often confined to representation of extreme events of defined return periods, or to what might be loosely termed morphological average conditions.

Known responses under defined storm conditions may often be used to calibrate models prior to testing alternative design configurations. On some occasions tests may replicate conditions that occur fairly frequently, with a view to determining alarm conditions.

A limitation of the physical model is its inability to retest scenarios once the model has been decommissioned. Physical modelling may therefore be most beneficial near to the end of the design process to aid refinement of understanding gained from prior numerical or empirical techniques, or in conjunction with those by feeding information into their calibration or development. Physical models are particularly valuable for the refinement of design details and optimising solutions.

8.2.2 Beach profile

Models constructed in a wave flume can be particularly useful to help understand cross-shore beach response, being better for replicating the characteristics of the beach for varying conditions than empirical approaches. But with physical models of beaches, it is necessary to carefully consider limitations due to the implications of scale effects which can affect the profile response of the beach within the model.

There are currently no established methods for scaling of mixed sand and gravel sediments that enable correct sediment motion and permeability to be achieved. This means that modelling of shingle beaches is restricted to coarser grained materials ($D_n > 4$–6 mm), as it is not usually possible to accurately scale finer sediment. Under these circumstances the indigenous or design grading curve is truncated at this sediment cut-off size and only the coarser fraction is replicated.

This means that the size and properties of sediment in physical models have to be compromised and in particular the behaviour of mixed beaches cannot be particularly well replicated. In these cases the use of different material sizes will affect the permeability and behaviour of the beach and therefore the confidence placed in results should be regarded in that context.

Where the actual beach is of mixed sediment sizes, differences in the upper beach from that in the model should be expected due to the differences in permeability. The reduced permeability results in wave run-up being higher than on very permeable beaches. The combination of the reduced slope and increased run-up elevation on a mixed beach means that the crest will also form further to landwards than on a pure shingle beach. Alternatively near vertical slopes may arise due to the matrix and cliffing effects of mixed sand and gravel. The lower beach should be expected to be flatter than in the model due to the finer material which reduces the permeability. These issues can be exacerbated when moving to full scale construction phase when beach recharge is invariably constructed with material of a different grade to that tested (for example, at Preston Beach).

8.2.3 Beach plan shape

Although three-dimensional physical models can represent wave processes better than numerical models, they are not normally expected to provide precise results for sediment transport on sand and mixed beaches due to the scaling issues. The inability to quickly adjust combinations of water level and wave conditions within physical models also means that numerical plan shape models can be better suited to examination of the long-term plan shape evolution.

However, beach plan shape may evolve differently close to structures and the physical model does provide a good representation of the wave processes in these areas. A key advantage of the physical model is the ability to reproduce small and complex features, such as the geometry of complex sediment control structures or where features such as the slope or height of the structure are significant. Similarly complex changes to the alignment of structures can be represented. This is a limitation of numerical models so the optimum solution can be to use a three-dimensional physical model in conjunction with a beach plan shape model used to calibrate sediment transport in the physical model. Llandudno North Shore provides an illustration of this approach.

While it is often desirable to represent the whole of a frontage, scaling laws and the size of test facilities often restrict the opportunity to do this. Instead it is frequently necessary to model only a representative section of the frontage within the physical model, as was the case for Hurst Spit and Seaford.

Table 8.1 Overview of wave basin physical models

Description	3D scaled physical copy of the beach and structures of major schemes and simulation of physical processes, using a wave basin to predict beach plan shape changes
Applications	For schemes with complicated or irregular bathymetry or with control structures (for example, to investigate the development of a beach behind or adjacent to detached breakwaters or next to a rock groyne) Useful where beaches are affected by both waves and currents and where turbulence and other non-linear physical processes are important or where seepage and run-up flow fields interact. Used to answer questions arising from unforeseen consequences of schemes. To assess the local influences of structures, performance and scour
Temporal applicability	Short-term
Spatial applicability	Hundreds of metres
Inputs	Physical reproduction of bathymetry Multi-directional waves, for particular storms or morphological design wave conditions
Computing requirements / calculations	Physical model construction Scaling of beach material Definition, and scaling of, wave climate
Outputs	Photographic and measured topographic data of changes to beach from applied waves.
Assumptions	Sediment size is scaled
Strengths	Ability to include and combine many physical processes High degree of control that allows simulation of varied and extreme conditions. Can assess short-term changes to infrequent severe events outside the range of numerical models. Gives visual qualitative feedback. Allows testing of alterations to schemes. Valuable to examine the local beach response to the influences of control structures and changes in their geometry Able to examine behaviour in a 3D environment. Can be used to validate numerical models. Combined with numerical modelling to predict long-term changes.
General	Costs and time to conduct a physical model are high compared with

limitations	numerical modelling. Impractical and expensive to model more than a few wave conditions from a limited range of directions and water levels Predicts beach changes over a short period of time, need to be combined with numerical modelling for long-term changes. Scale effects can affect accuracy, for example, sediment size and transport. Laboratory effects induced by model boundaries can influence the process. Unrealistic forcing conditions can influence the process. Difficulties can arise if the modelling needs to be re-run at a later date. Models built to a smaller scale than 1:40 are likely to experience significant scale effects.

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010) relevant studies (Environment Agency, 2009, 2010a, 2011a, 2011b, 2011c) and user experience.

Table 8.2 Overview of wave flume physical models

Description	2D scaled physical copy of the beach and structures and simulation of physical processes, using a wave flume to predict short-term beach profile changes (including overwashing and barrier breaching)
Applications	Used for beach recharge schemes to assess response of newly placed material. To investigate the performance of an existing beach, sometimes fronting a seawall/revetment Used to answer questions arising from unforeseen consequences of schemes.
Temporal applicability	Short-term (event specific)
Spatial applicability	Single location(s) along a beach
Inputs	Physical reproduction of (usually simplified) bathymetry Physical reproduction of waves
Computing requirements / calculations	The model is run for a variety of storm conditions over short periods of time
Outputs	Changes in beach profile Rates of overtopping/response of beach crest
Assumptions	Local processes are uniform and therefore longshore processes are omitted. Sediment sizes are scaled.
Strengths	Can be used to validate numerical models. Combined with numerical modelling to predict long term changes. Ability to observe and better understand the physical processes High degree of control that allows simulation of varied and extreme conditions. Can assess short-term changes to infrequent severe events outside

	the range of numerical models. Gives visual qualitative feedback. Allows rapid testing of alternatives. Easier to set up and run than wave basin models
General limitations	Costs and time to conduct a physical model may be high compared with numerical modelling and will be higher than an empirical model. Predicts beach changes over a short period of time; these need to be combined with numerical modelling for long-term changes. Scale effects can affect accuracy, for example, sediment size and transport. Cannot model finer sediment sizes (generally below 4–6 mm) so may not represent whole beach grading. Limited scope to re-run model at a later date without full reconstruction Models built to smaller scales are likely to experience significant scale effects Only able to examine behaviour in a 2D environment.

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010) relevant studies (Environment Agency, 2009, 2010a, 2011a, 2011b, 2011c) and user experience.

9 Beach design based on measurement techniques

9.1 Overview

Some beach schemes are designed and managed purely, or predominantly, from the interpretation of measured data. This is less common but does have the advantage that the data used are specific to the behaviour of that particular beach. However, this approach is reliant on:

- the extent of the past information that is available
- an assumption that this information is representative of future conditions
- appropriate interpretation, for example, being able to differentiate between trends and episodes

9.1.1 Beach monitoring data

The use of monitoring data to inform beach design and maintenance involves the analysis of beach survey information to predict changes at a specific site.

Where there are several years of comprehensive beach survey data, combined with a good record of beach management activities during that period, this can be an effective means to understand beach behaviour and thus estimate future response and management requirements.

Table 9.1 provides an overview of using monitoring data for beach design and maintenance, including its applicability, inputs, outputs, assumptions, strengths and limitations. Figure 9.1 shows an example of the use of monitoring data for beach management.

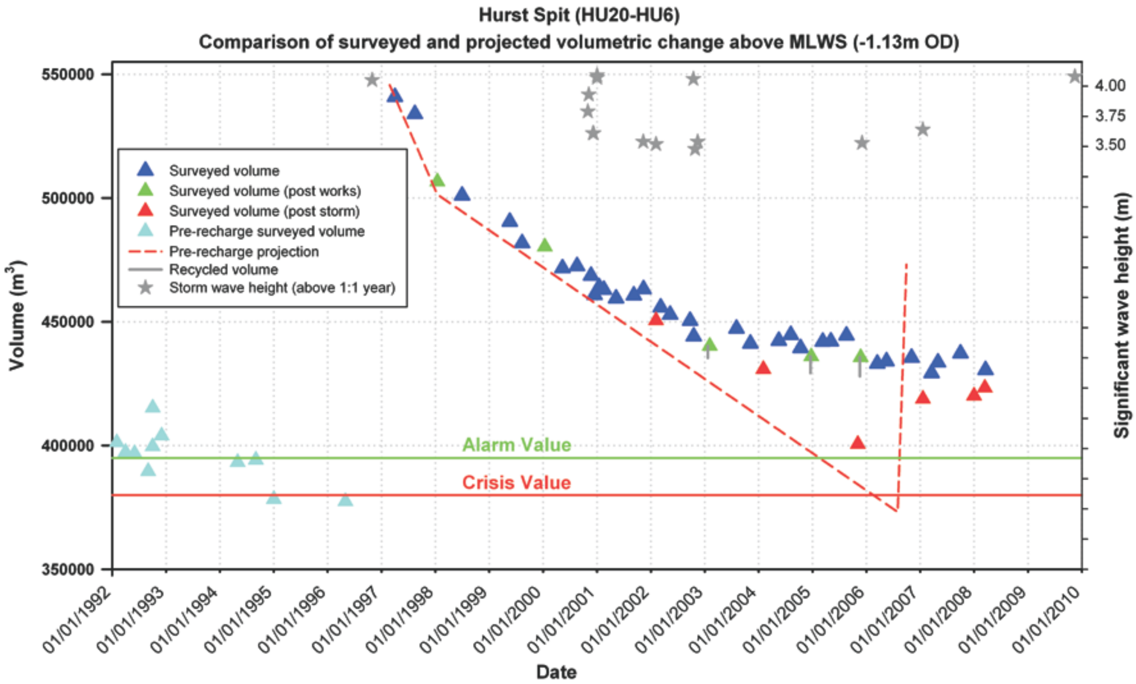

Figure 9.1 Example of the use of monitoring data for beach management (from CIRIA 2010)

9.1.2 Historical trend analysis

Historical trend analysis to inform beach design and maintenance involves the analysis of historical data relating to morphological features to identify trends and rates of change at a specific site. Typically this will be mapped or readily observed features such as high water or low water positions or ridges/runnels from maps or aerial photographs.

Table 9.2 provides an overview of using historical trend analysis for beach design and maintenance, including its applicability, inputs, outputs, assumptions, strengths and limitations.

No review of historical trend analysis was carried out within the case study comparative analysis and so observations on these are therefore limited.

9.2 Observations on use

9.2.1 Interpretation of beach monitoring data

Unlike models which have constraints and require calibration to 'fit' the beach behaviours, monitoring information provides an actual record. However, this actual record is only a series of snapshot conditions at certain times and may not be representative of all states of the beach between surveys.

Where available, long-term monitoring datasets can be used to reliably indicate long-term trends of sediment drift and plan shape changes. If possible these data should include any fixed structures beyond which sediment is unable to travel. Often this is not the case and interpretation of sediment transport can be made only on the basis of the longshore variability of inflexions in beach profile changes over time. Similarly the sediment input to the beach from the updrift and offshore directions must be established.

Using this to provide a longer term forward look does require expert interpretation; it is essential to understand why past changes have occurred and whether they would occur again. Also, where a future management approach is going to change from that in the past (for example, to control structures), then this approach has limitations.

Ideally a beach designed solely on past monitoring data would be based upon a long-term record (>20 years) to provide a sufficient degree of confidence in the outputs and address annual variability. Even then it is strongly advised that a good appreciation of the corresponding environmental conditions (that is, wave activity) is also obtained. More commonly this information might be used in conjunction with numerical models and empirical tools and techniques to develop the beach scheme. It also assists greatly in providing confidence in future predictions. The Lincshore and Bournemouth case studies both provide excellent examples of using long-term monitoring records.

Figure 9.2 shows a further example of the use of monitoring data.

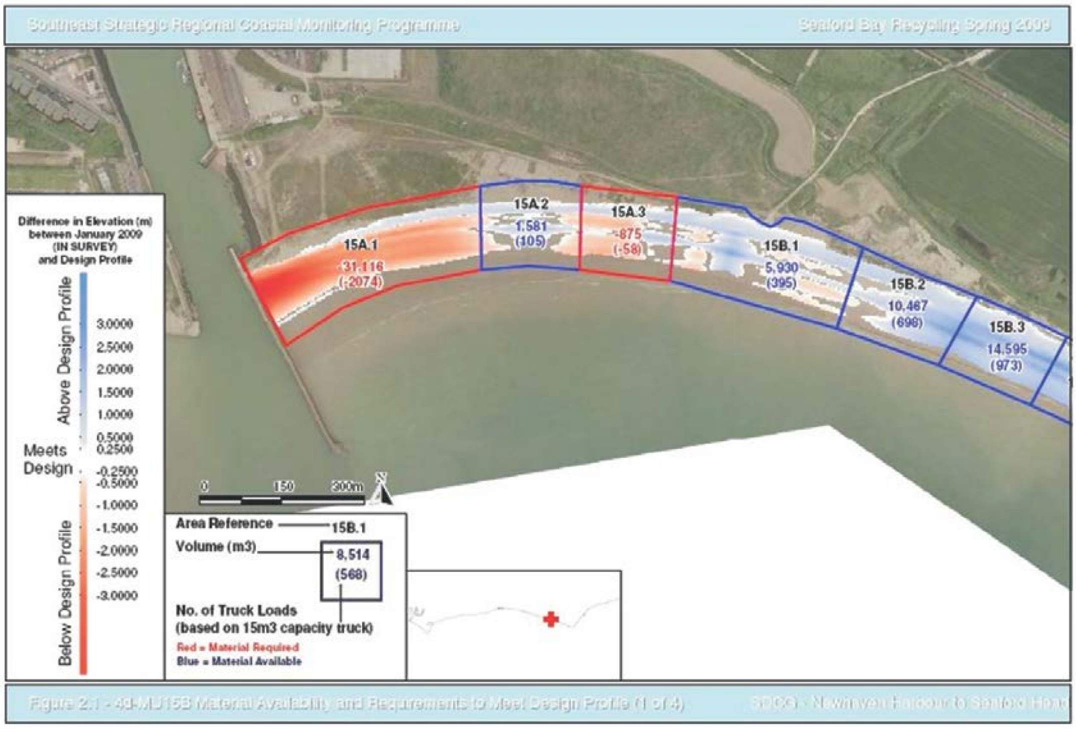

Figure 9.2 Example of using monitoring data (from CIRIA 2010)

9.2.2 Interpretation of historical data

Usually these data are only available in time steps of several years, so this approach tends to be more useful to look at longer term underlying shoreline response rather than annual beach management campaigns. It can nonetheless be extremely useful to understand how a beach has responded to processes and past management activities, and thus guide how that beach might perform in the future, particularly if used in conjunction with empirical tools and techniques to develop the beach scheme. The Southend scheme, for example, used an understanding of the behaviour of other beaches in the area to support its design. Figure 9.3 shows an example of using historical data.

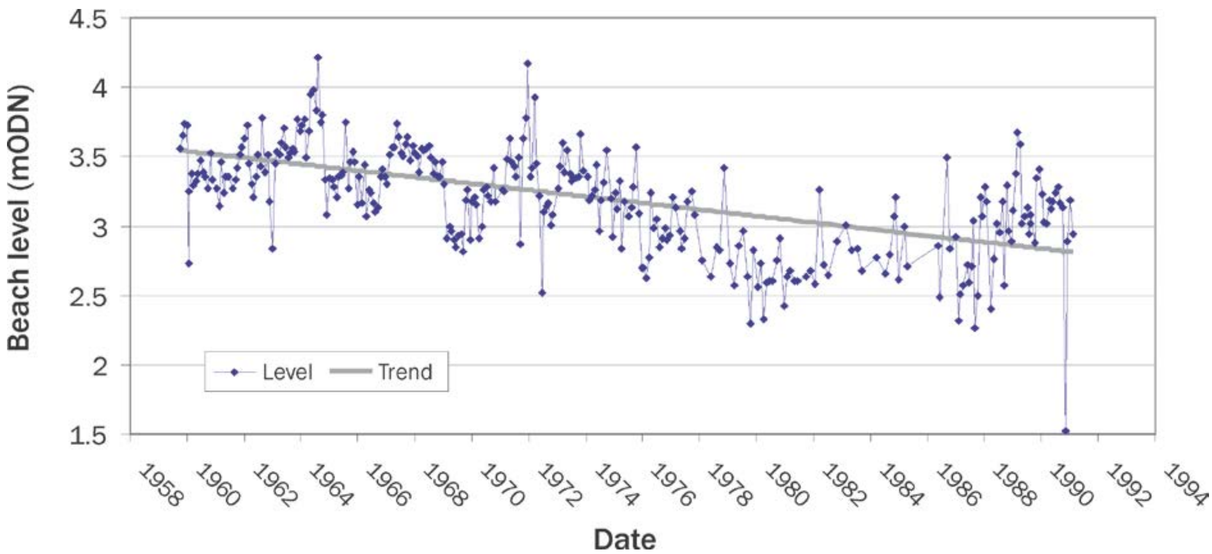

Figure 9.3 Example of using historical data (from CIRIA 2010)

Table 9.1 Overview of use of monitoring data for beach design and management

Description	Analysis of beach survey data to predict future beach behaviour to directly inform beach design and future maintenance activities
Applications	Analysis of measured beach profile data to assess past and current change Analysis of beach recycling or channel dredging data to determine sediment transport rates
Temporal applicability	Assessments are limited by the length of time monitored.
Spatial applicability	Metres to kilometres (site-specific)
Inputs	Beach profiles, wave and water level data, beach management data
Computing requirements / calculations	Analysis of monitoring data may involve simple (linear trend analysis) or more complicated methods (eigen-function analysis) and may also involve the use of additional software to input data, carry out analysis and establish trends in coastal response.
Outputs	Assessment of beach change or erosion and accretion rates
Assumptions	Assumes that the beach and forcing conditions will remain the same in the future.
Strengths	Monitoring data will relate to the behaviour of a specific beach. Monitoring data can be used to validate/calibrate other models.
General limitations	Uncertainty over which parameters are captured. Inherent lack of detail and therefore reduced accuracy Inability to distinguish between trends versus episodes Need for long-term datasets

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010) relevant studies (Environment Agency, 2009, 2010a, 2011a, 2011b, 2011c) and user experience.

Table 9.2 Historical trend analysis for beach design and maintenance

Description	Analysis of historical data to identify trends and rates of change relating to physical processes or morphological features to help predict future change
Applications	Identification of areas of erosion/recession and deposition/ progradation over time To assess changes in shoreline position
Temporal applicability	Decades
Spatial applicability	Specific features or whole beach over kilometres
Inputs	Maps and charts Aerial photography Surveys (for example, topographic, hydrographic, LiDAR) Anecdotal evidence

Computing requirements / calculations	Analysis of historical positional data using GIS, other software and methods Expert assessment and interpretation
Outputs	Erosion/accretion Shoreline position trends Shoreline movement trends
Assumptions	Assumes that the beach and forcing conditions will remain the same in the future.
Strengths	Historical data will relate to the behaviour of a specific beach. Complements longer-term geological analysis approaches. Provides key input to establishing a conceptual understanding of longer-term beach behaviour. May aid interpretation of model results.
General limitations	Availability and accuracy of historical data Uncertainty over which parameter is captured Inherent lack of detail over short timescales and therefore reduced accuracy Inability to distinguish between trends versus episodes Need for long-term datasets Past trends do not always indicate future behaviour. Ambiguity in interpretation of data

Notes: Summarised from the *Beach Management Manual* (CIRIA 2010) relevant studies (Environment Agency, 2009, 2010a, 2011a, 2011b, 2011c) and user experience.

10 Waves for beach modelling

10.1 Significance of wave climate for beach modelling

An appreciation of the wave climate is essential to predict beach behaviour. Wave action and longshore currents are the fundamental drivers of alongshore sand and shingle beach processes, and the majority of models used in beach design are driven by waves. Wave climate data are required even when applying empirical models or expert judgement.

Possible exceptions might be where there are considerable monitoring records upon which to design the beach management; although even then it can be useful to understand any changes in beach behaviour. Or, where there are good measured data at the shoreline itself (rare), or where the beach behaviour is simple and well-observed, and the scheme itself has built in flexibility to adapt to variable conditions. Understanding the wave conditions can also help manage these latter situations most cost-effectively.

The consequences of wave climate variability on beach modelling are assessed in each of the case studies. These conclude that variability of actual beach performance, relative to modelled expectations, can be attributed largely to differences in wave climate in many cases. For example, at Seaford the wave climate post-construction has been more energetic than modelled, while at Hurst Spit the wave climate is more bimodal. This has also been demonstrated at several sites by substitution of measured or hindcast wave data for modelled data to retrospectively assess performance, for example, Seaford and Hurst Spit. There is little doubt that the quality of input wave data has a major impact on the accuracy of the beach modelling.

10.2 Wave data

10.2.1 Selecting a representative time series

Case study assessments for some of the sites revealed that the conditions used in beach modelling were not representative of those that have occurred following construction. Data captured for south coast locations, for example, was somewhat less severe during the 1970s than subsequently occurred in the 1980s and 1990s. The implication of the use of these datasets is that sediment transport rates have been higher than predicted by the design phase modelling. In some instances sediment transport rates have more than doubled, for example, at Seaford (Millard and Brampton 1996) where post-scheme modelling has replicated the actual wave conditions and shown the dramatic impacts of the more severe wave climate.

This difference demonstrates the need to use as long datasets as possible. The assumption is often made that the wave climate is static, although numerous examples suggest that this is not the case. There is evidence of significant climate variability over lengthy periods, perhaps extending for more than a decade. Longer term records are more likely to capture such variability.

Hindcast synthetic wave climates derived from wind data are generally based on records from long-term meteorological stations. In some instances the available data may be derived from short durations of wind data of less than five years. Generally longer records of more than 15 years are desirable to identify inter-decadal variability, as well as inter-annual variability of wave climate, but 10 years is generally sought as a minimum. Long-term records also enable more reliable assessments of the frequency and variability of storm intensity and a preliminary estimate of any longer term climate change patterns. They also provide the opportunity for more reliable determination of typical extreme design conditions with longer return periods (1:100 or 1:200 years) as used typically in coastal engineering design.

Box 10.1: Wave data for beach modelling

Deep water synthetic wave data are is now available from models for the whole of the open coast of the UK for the period extending from 1988 to the present day on a 25 km grid (although it is best to not rely on data pre-1990) and on a 12 km grid dating back to the mid-2000s. Some of the case study sites pre-date the introduction of the Met Office's second generation wave models and it is not appropriate to consider these in context with more recent schemes that derive benefits from such long-term records. The benefit of such a data source is that several decades of data are available and the issue of inter-decadal variability of wave climate can now be assessed systematically over a period of over 20 years.

A more recent generation of wave model was introduced into the operational suite of models run by the Met Office in 2008, WAVEWATCH III. Validation of this model has been undertaken of this model on a dataset of three years' length (Bradbury and Mason 2012). Comparisons of hindcasts with measured data on the south coast are very encouraging with the model significant wave height bias evident in earlier models being eliminated from this generation (whether this holds true for other coasts is not known). However, the models perform less efficiently in forecasting mode. The dataset is of insufficient length to enable validation of more extreme events at this stage. Regrettably the representation of wave period seems little better than earlier generations of models, which typically overpredict wave period (Tz) by around 20%, despite the much improved frequency resolution.

The Environment Agency is currently commissioning a long-term hindcast of wave data using the WAVEWATCH III model and this is likely to provide a nationally consistent offshore dataset extending over a duration of approximately 30 years. In doing so, it is essential that the calibration/validation of the models is well documented.

There is also clear benefit in breaking the datasets down into periods of energetic and less energetic conditions to enable the variability of sediment transport rates to be modelled more accurately. The issue of short duration non-representative wave climates is generally best examined by sensitivity testing of a range of conditions, in addition to those derived from the transformed hindcasts.

Figure 10.1 shows an example comparison of wave climate data.

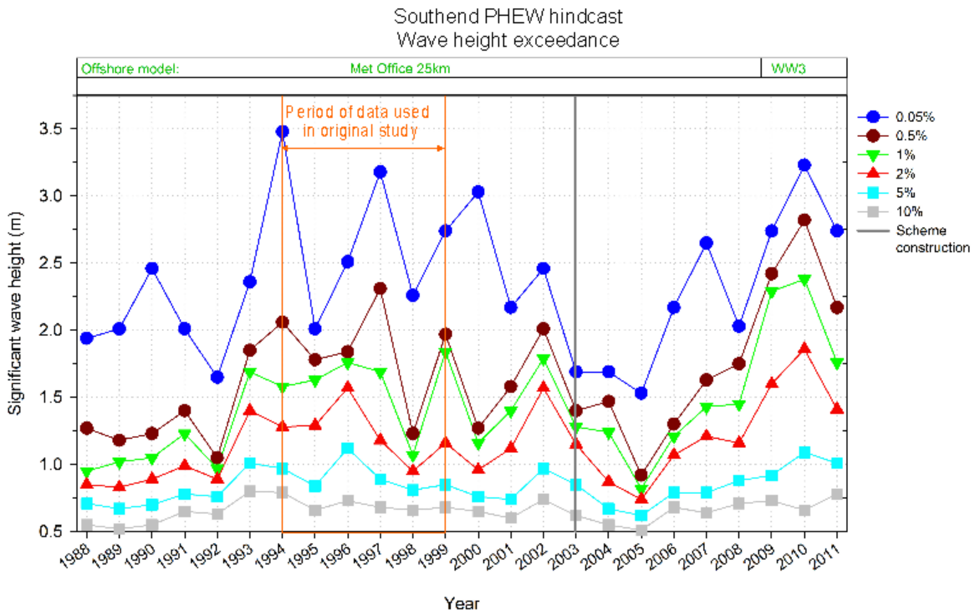

Figure 10.1 Example of comparing wave climate data

10.2.2 Wave climate validation

Direct measurements of wave data are used infrequently in beach modelling, primarily because sufficiently long data records are rarely available to provide a suitable length of time series that is likely to be representative of future trends, or to enable reliable determination of extreme conditions. However, the accuracy of hindcasting and transformation modelling, relative to measured wave data, is highly significant since sediment transport models are energy-based with a high dependence on significant wave height, wave period spectrum and wave direction.

Where measured data are available, this presents some significant benefits by comparison with synthetic wave datasets. Even short lengths of measured data are extremely valuable for calibration and validation of synthetic wave data.

Suitable wave data were not available to validate synthetic wave data at the design stage for many of the case study sites, but considerable post-scheme data are now available to enable a systematic comparison of measured and modelled wave data.

Box 10.2: Example of beach response sensitivity to wave climate

Bradbury et al. (2006b) noted significant differences in wave climate characteristics when comparing transformed wave data from the UK Met Office 25 km wave model with measured data at numerous south coast locations. A systematic region wide bias in the model output was identified. The model overpredicts significant wave height (Hs) when 0.5 m < Hs < 2 m; this range of conditions is typical of those expected to result in longshore transport of shingle. Wave height and direction are the key drivers of sediment transport. Sensitivity tests conducted to assess the impacts of such variability on drift rates for a test site beach plan shape model suggested that the more energetic modelled data resulted in 40% greater sediment transport rates than derived when using the directly measured data. Such a bias in the modelled wave data could be removed by calibration of the wave model relative to the measured data. The same model similarly underpredicts the more extreme significant wave heights, which has implications for cross-shore modelling of profile response or breach assessment and to a lesser extent for longshore sediment transport.

10.2.3 Considering different wave climates

Some of the earlier projects assessed in the case studies did not include consideration of swell waves and it is noted that, where cross-shore processes such as run-up and breaching are important, these processes have been reproduced inadequately. Wind waves and swell waves may also have different directional characteristics leading to quite different beach response to each.

Bimodal wave conditions

Observations made in conjunction with the regional coastal monitoring programmes have identified a systematic pattern of wave conditions characterised by bimodal wave periods through the English Channel (Mason et al. 2009). Figure 10.2 shows an example bimodal wave spectrum.

Field data (Bradbury et al. 2011) shows that bimodal waves can have significant bearing on beach response and modelling needs to consider beach response to both. To date it seems that such conditions have not been considered in site-specific design of beach management schemes, despite the possibility that standards of service may be considerably lower under these conditions than standard design criteria might suggest.

There is evidence that the beach will respond somewhat differently to these conditions than when subjected to wave conditions characterised by a simple spectral shape. Earlier research (Coates and Hawkes 1998) had suggested that this may be a problem, but it is only since the recent detailed observations in the English Channel that this seems to have been considered seriously. The Environment Agency has recently approved funding for a series of physical model investigations to examine and quantify the cross-shore impacts of these conditions; these cannot currently be assessed with any of the available cross-shore models.

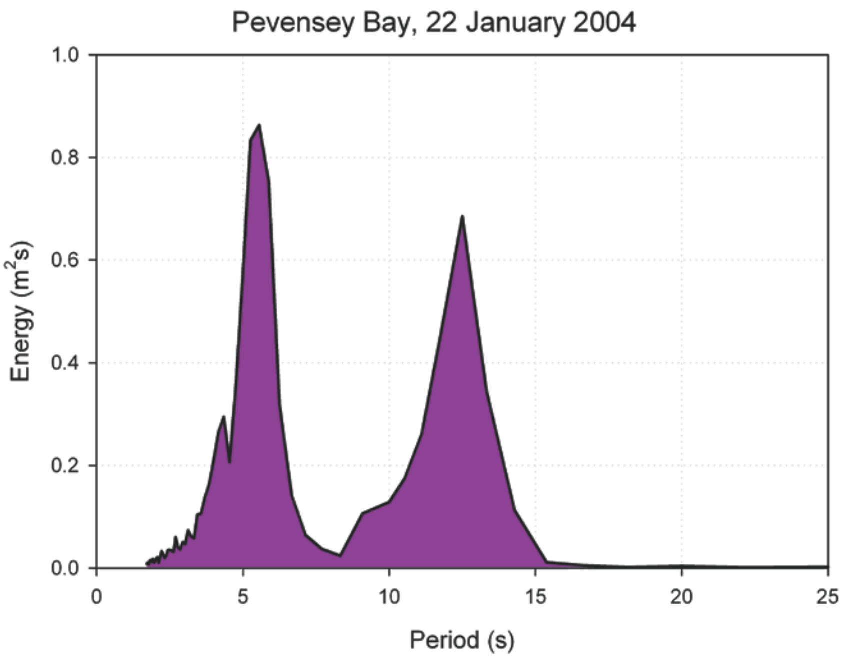

Figure 10.2 Example of bimodal wave spectrum (from CIRIA 2010)

10.2.4 Future wave conditions

The modelled wave climate will ideally be representative of future conditions, particularly if the beach modelling is to be used to assess future developments. This is difficult to achieve, however, simply because future change in climate is unknown and so this issue can only be addressed through sensitivity testing. In contrast this has only limited significance when the beach model is used to assess the relative performance of different beach management schemes.

10.3 Wave transformation

10.3.1 Considerations on wave transformation approach

The sensitivity of beach changes to wave action means that the approach to wave modelling, and the derived wave conditions can have impacts on beach modelling outputs.

It is usually necessary to transform the source wave data from a deep water offshore location to suitable nearshore locations for subsequent input to the beach process models. Transformation models generate the appropriate inshore wave climate by replicating the processes of refraction, diffraction, shoaling, breaking and friction as waves move into shallower water and approach the shoreline.

The choice of wave modelling needs to be appropriate to deliver the outputs for the type of beach modelling that will be undertaken.

Numerical beach plan shape models are effectively driven by the wave model used to derive nearshore wave conditions. Therefore incorporation of the full distribution of potential wave height, period and directions in the wave model is essential (CIRIA 2010). These models are particularly sensitive to small changes in direction and wave height and are driven typically by time series of several years' continuous data.

Empirical plan shape models are less sensitive and are more likely to require typical or average conditions. They therefore need details on the levels of wave energy coming from different sectors.

Cross-shore and physical models are typically used to assess the impacts of specific events and require accurate projections of wave height and period combination. These often focus on the more extreme conditions, which are usually derived from extrapolations of probability distributions of offshore wave conditions transformed to inshore. Cross-shore storm response modelling also needs careful consideration of design water levels, surge profile and timing of storm profile. Details on extreme water levels and standard surge profiles are provided in Environment Agency (2011b, 2011d).

10.3.2 The importance of bathymetry

The output from wave transformation models is highly sensitive to:

- the bathymetry
- roughness coefficients used where wave breaking may be significant
- water levels used in the model

If these are not accurate then the directional shifts and energy changes of the waves will not be well replicated.

Particularly for beach plan modelling and drift calculation, wave angle to the beach can be the single greatest influence on outputs. Good definition of wave direction at the shoreline is therefore critical as small differences in wave angle of just 1–2^{o} can produce significant differences in alongshore transport rates and potentially even conclusions made on net drift direction.

Accurate reproduction of up-to-date bathymetry is therefore important and it is essential that the model set-up considers the resolution and currency of the bathymetry data and utilises a suitable grid to define this within the model. Unfortunately, nearshore bathymetry data are not often current or regularly maintained. Inshore bathymetry is rarely updated, usually less frequently than once every five years. Where information is old or questionable, or the seabed is thought to have changed, consideration might be given to commissioning an up-to-date inshore bathymetric survey.

The introduction of multi-beam bathymetric surveys to many monitoring programmes provides an opportunity to assess the potential bed composition and mobility, and therefore to assess the risk of changing bathymetry.

Box 10.3: Future bathymetric changes

For longer term beach management, the potential for future changes to the bathymetry should be considered. But it is not possible to create a future bathymetry with any degree of confidence, so future wave action at the shoreline will also be subject to uncertainty. A judgement call needs to be taken on what future changes could occur and their significance; past information from older surveys can help to inform this. Where a site does have a particularly mobile seabed, for example, where offshore banks change position and elevation, then it may be prudent to model more than one bathymetry to determine the scope and extent of potential changes in beach behaviour and its management in the future. Future changes seawards of the beach should also be considered, for example, those due to migration of offshore banks, mining subsidence and impacts of sea level rise.

References

AXE, P., ILIC, S. and CHADWICK, A, 1996. *Evaluation of beach modelling techniques behind detached breakwaters.* In *Coastal Engineering 1996*, Proceedings of 25th International Conference on Coastal Engineering (2-6 September 1996, Orlando, FL), pp. 2036-2049. New York: American Society of Civil Engineers.

BLANCO LOPEZ DE SAN ROMAN, B., COATES, T. T., HOLMES, P., CHADWICK, A. J., BRADBURY, A. P., BALDOCK, T., PEDROZO-ACUNA, A., GRUNE, J. and LAWRENCE, J., 2006. Large wave channel (GWK) experiments on gravel and mixed beaches: experimental procedure and data documentation. *Coastal Engineering*, 53 (4), 349-362.

BRADBURY, A.P., COPE S.N. and PROUTY, D.B., 2006a. *Predicting the response of shingle barrier beaches under extreme wave and water level conditions in southern England*. In *Coastal Dynamics 2005*: *State of the Practice* (ed. A. Sanchez-Arcilla), Proceedings of 5th International Conference on Coastal Dynamics (4-8 April 2005, Barcelona). New York: American Society of Civil Engineers.

BRADBURY, A.P., MASON, T.E. and HOLT, M.W., 2006b. *Comparison of the performance of the Met Office UK-Waters Wave Model with a network of shallow water moored buoy data.* In Proceedings of 8th International Workshop on Wave Hindcasting and Forecasting (14-19 November 2004, Oahu, Hawaii). Geneva: World Meteorological Organization.

BRADBURY, A.P., MASON, T.E., and PICKSLEY, D., 2010. *A performance based assessment of design tools and design conditions for a beach management scheme*. In *Coasts, Marine Structures and Breakwaters*: *Adapting to Change*, Proceedings of 9th International Conference (16-18 September 2009, Edinburgh), ed. N.W.H. Allsop, Volume 2, pp. 338-351. London: Thomas Telford/Institution of Chemical Engineers.

BRADBURY, A.P., STRATTON, M., and MASON, T.E, 2011. Impacts of wave climate with bimodal wave period on the profile response of gravel beaches. In *Coastal Sediments '11*, Proceedings of 7th International Symposium on Coastal Engineering and Science of Coastal Sediment Processes (2-6 May 2011, Miami, FL). New York: American Society of Civil Engineers.

BRADBURY, A.P. and MASON, T.E., 2012. *Improving modelled nearshore wave climate and forecasts in southern England with a network of buoy data*. In Proceedings of 12th International Workshop on Wave Hindcasting and Forecasting (30 October – 4 November 2011, Kona, Hawaii). Geneva: World Meteorological Organization.

BRAMPTON, A.H. and MILLARD, K., 1996. The effectiveness of the Seaford Beach Renourishment Programme. In *Partnership in Coastal Zone Management* (ed. J. Taussik and J. Mitchell), pp. 623-620. Cardigan: Samara Publishing.

BRAMPTON, A.H. and SOUTHGATE, H.N., 2001. *Coastal Morphology Modelling: A Guide to Model Selection and Usage,* Report SR 570. Wallingford, Oxfordshire: HR Wallingford.

CARTER D., BRAY, M. and HOOKE, J., 2004. *SCOPAC Sediment Transport Study, 2nd edition*. Report by RACER to Standing Conference on Problems Associated with the Coastline (SCOPAC).

CIRIA, 2010. *Beach Management Manual,* 2nd edn. C685. London: CIRIA.

COATES, T.T. and HAWKES, P.J., 1998. *Beach recharge design and bimodal wave spectra*. In *Coastal Engineering 1998* (ed. B.L. Edge), Proceedings of the 26th

International Conference on Coastal Engineering (22-26 June 1998, Copenhagen), New York: American Society of Civil Engineers.

DEAN, R.G., 1997. *Equilibrium Beach Profiles: US Atlantic and Gulf Coasts*. Ocean Engineering Report No.12. Newark, DE: Department of Civil Engineering, University of Delaware.

ENVIRONMENT AGENCY, 2009. *Characterisation and Prediction of Large-scale, Long-term Change of Coastal Geomorphological Behaviours: Final Science Report.* Joint Defra/Environment Agency Flood and Coastal Defence R&D Programme. Science Report SC060074/SR1. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2010a. *Flood and Coastal Risk Management Modelling Strategy 2010-2015.* Bristol: Environment Agency. Available online at: http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/geho0310bsbt-e-e.pdf. Date accessed: 12th September 2013.

ENVIRONMENT AGENCY, 2010b. *Guidance for Outline Design of Nearshore Detached Breakwaters on Sandy Macro-tidal Coasts*. Joint Defra/Environment Agency Flood and Coastal Defence R&D Programme. SC060026/R1. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011a. *Dealing with Sandy Coasts – New Methods from SANTOSS Research Project.* Joint Defra/Environment Agency Flood and Coastal Defence R&D Programme. SC060027. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011b. *Coastal Flood Boundary Conditions for UK Mainland and Islands Project: Practical Guidance Design Sea Levels.* Joint Defra/Environment Agency Flood and Coastal Defence R&D Programme. SC060064/TR4. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011c. *Coastal Flood Boundary Conditions for UK Mainland and Islands Project: Design Swell Waves*. Joint Defra/Environment Agency Flood and Coastal Defence R&D Programme. SC060064/TR3. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2011d. *Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities*. Bristol: Environment Agency.

FLEMING, C.A., 1990. *Guide on the Use of Groynes in Coastal Engineering.* Report R119. London: CIRIA.

HALCROW, 2002. *Futurecoast – Predicting Future Shoreline Evolution*. London: Defra.

HALCROW, 2010. *Dawlish to Teignmouth Seawall Feasibility Study*. Report to Network Rail.

HALCROW, 2013. *Dawlish Warren and Exmouth Beach Recharge Technical Appraisal Study: Numerical Modelling Report.* Report to Teignbridge District Council, Newton Abbot.

HSU, J.R.C. and EVANS, C., 1989. Parabolic bay shapes and applications. *Proceedings of the Institution of Civil Engineers*, 87 (4), 557-570.

MASON, T., BRADBURY, A., POATE, T. and NEWMAN, R., 2009. *Nearshore wave climate of the English Channel – Evidence for bimodal seas.* In *Coastal Engineering 2008* (ed. J. McKee Smith), Proceedings of the 31st International Conference on Coastal Engineering (31 August – 5 September 2008, Hamburg), pp. 605-616. New York: American Society of Civil Engineers.

PELNARD-CONSIDERE, R., 1956. Essai de theorie de l'evolution des forms de rivages en plage de sable et de galets. Fourth Journel fe l'Hydraulique, les energies de la Mer, Question III, Rapport No. 1, 289-298 [In French].

POWELL, K.A., 1990. *Predicting Short-term Profile Response of Shingle Beaches*. Hydraulics Research Report SR 219. Wallingford, Oxfordshire: HR Wallingford.

SILVESTER, R. and HSU, J.R.C., 1997. *Coastal Stabilisation*. Advanced Series on Ocean Engineering. Volume 14. Singapore: World Scientific.

SPATARU, A.N., 1990. Breakwaters for the protection of Romanian beaches. *Coastal Engineering*, 14 (2), 129-270.

US ARMY CORPS OF ENGINEERS, 2002. *Coastal Engineering Manual*. Engineer Manual 1110-2-1100. Parts I–VI. Washington, DC: US Army Corps of Engineers. Available from: http://publications.usace.army.mil/publications/eng-manuals/ [Accessed August 2013].

VAN WAVEREN, R.H., GROOT, S., SCHOLTEN, H., VAN GEER, F.C., WÖSTEN, J.H.M., KOEZE, R.D. and NOORT, J.J., 1999. *Smooth Modelling in Water Management. Good Modelling Practice Handbook.* STOWA report 99-05. Dutch Department of Public Works, Institute for Inland Water Management and Waste Water Treatment, Report 99.036. Amersfort, The Netherlands: STOWA/RIZA.

VELLINGA, P., 1984. A tentative description of a universal erosion profile for sandy beaches and rock beaches. *Coastal Engineering*, 8 (2), 177-188.

Glossary

Term	Definition
Accretion	Accumulation of sediment due to the natural action of waves, currents and wind.
Alarm level / threshold	The level before crisis level/threshold. This is usually a predetermined value where the monitored beach parameter falls to within range of the crisis level, but has not resulted in systematic failure of the function being monitored, for example, recession of a beach crest eroding to within 10 m of an asset, where it has been predetermined that an extreme storm event could result in recession of 5 m. The alarm level in this example is therefore a 5 m buffer. Increased monitoring would be required when an Alarm Level is compromised and intervention undertaken if deemed necessary. Managing alarm levels can be planned in advance.
Barrier beach	A sand or shingle bar above high tide, parallel to the coastline and separated from it by a lagoon.
Beach	A deposit of non-cohesive material (for example, sand, gravel) situated on the interface between dry land and the sea (or other large expanse of water) and actively ‘worked’ by present day hydrodynamic processes (that is, waves, tides and currents) and sometimes by winds.
Beach control structures	Beach control structures are used to inhibit or control the rate of sediment transport along the coastline.
Beach management	The process of managing a beach, whether by monitoring, simple intervention, recycling, recharge, the construction or maintenance of beach control structures or by some combination of these techniques in a way that reflects an acceptable compromise in the light of available finance, between the various coastal defence, nature conservation, public amenity and industrial objectives.
Beach Management Plan (BMP)	A BMP provides a basis for the management of a beach for coastal defence purposes, taking into account coastal processes and the other uses of the beach.
Beach manager	A beach manager seeks to maintain or improve a beach as a natural/recreational resource, or as a means of coastal protection, while providing facilities that meet the needs and aspirations of those who use the beach.
Beach plan shape	The shape of the beach in plan; usually shown as a contour line, combination of contour lines or recognisable features such as beach crest and/or the still water line.
Beach profile	Cross-section perpendicular to the shoreline. The profile can extend seawards from any selected point on the landward side or top of the beach into the nearshore.

Term	Definition
Beach recharge (nourishment)	Artificial process of replenishing a beach with material from another source.
Beach recycling/ re-profiling	The movement of sediment along a beach area, typically from areas of accretion to areas of erosion, and shaping the beach profile to have a desired crest height, width and slope.
Berm	A ridge located to the rear of a beach, just above mean high water. It is marked by a break of slope at the seaward edge.
Bimodal wave period	Related to frequency distribution of waves, for each bimodal wave periods two wave peaks are observed.
Breaching	Failure of the beach head allowing flooding by tidal action.
Breakwater	A structure projecting into the sea that shelters vessels from waves and currents, prevents siltation of navigation channel, protects a shore area or prevents thermal mixing (for example, cooling water intakes). In beach management, breakwaters are generally structures protecting areas from the full effect of breaking waves. Breakwaters may be shore-attached and extended seawards from the beach, or may be detached and sited offshore, generally parallel to the beach, to provide sheltered conditions.
CIRIA	Construction Industry Research and Information Association
Cliffing	The development of almost vertical cliffs, up to 2 m high (although generally less than 1 m) following creation of a new beach slope after beach recharge. The cliffs occur at or above mean high tide, and are a result of mixing different sized sediments and compaction of material by mechanical plant.
Climate change	Long-term changes in climate. The term is generally used for changes resulting from human intervention in atmospheric processes through, for example, the release of greenhouse gases to the atmosphere from burning fossil fuels, the results of which may lead to increased rainfall and sea level rise.
Coastal cell	Coastline unit within which sediment movement is self-contained.
Coastal forcing (forcing factors)	The natural processes that activate coastal hydro- and morpho-dynamics (for example, winds, waves, tides).
Cohesive sediment	Sediment containing significant proportion of clays, the electromagnetic properties of which cause the sediment to bind together.
Crest	Highest point on a beach face, breakwater or seawall.
Crest level/height	The vertical level of the beach relative to metres Ordnance Datum (mOD).

Term	Definition
Crest width	The horizontal distance measured from the back of the beach to the top edge of the beach face slope – or on a barrier beach the distance between the top of the front slope and rear slope.
Crisis level / threshold	The level at which the function being monitored, such as the stability of the beach and/or any backing structures (seawall/promenade), could be compromised and emergency remedial action becomes necessary, for example, as in the case described under alarm level/threshold above, the beach crest recedes to within 4 m of an asset that requires protection, where it has been predetermined that an extreme event could result in 5 m of recession.
Crenulate bay	Term describing characteristic plan shape of equilibrium beach formed between two fixed headlands.
Cross-shore transport	Movement of material perpendicular to the shore.
Defra	Department for Environment, Food and Rural Affairs
Depth of closure	The 'seaward limit of significant depth change' – it does not refer to an absolute boundary across which there is no cross-shore sediment transport.
Drift-aligned	A coastline that is orientated obliquely to prevailing incident wave fronts.
Drift reversal	A switch of an indigenous direction of littoral transport.
Empirical modelling	Modelling using empirical relationships.
Environment Agency	UK non-departmental government body responsible for delivering integrated environmental management including flood defence, water resources, water quality and pollution control.
Erosion	Wearing away of the land, usually by the action of natural forces.
Flood and Coastal Risk Management	Flood and coastal risk management addresses the scientific and engineering issues of rainfall, run-off, rivers and flood inundation and coastal erosion, as well as the human and socio-economic issues of planning, development and management.
Geomorphology/ morphology	The branch of physical geography/geology which deals with the form of the Earth, the general configuration of its surface, the distribution of the land, water and so on
GIS	Geographical information system
Groyne	Narrow, roughly shore-normal structure built to reduce longshore currents and/or to trap and retain beach material. Most groynes are of timber or rock, and extend from a seawall, or the backshore, well onto the foreshore and rarely even further offshore.
Groyne bay	The compartment between two groynes.

Term	Definition
Hard defence	General term applied to impermeable coastal defence structures of concrete, timber, steel, masonry and so on which reflect a high proportion of incident wave energy.
Joint probability	The probability of two (or more) things occurring together.
Joint Probability Analysis (JPA)	Function specifying the joint distribution of two (or more) variables.
Joint return period	Average period of time between occurrences of a given joint probability event.
Locally generated (wind) waves	Locally generated short period and irregular waves created by the flow of air over water.
Longshore transport	Movement of material parallel to the shore – also referred to as longshore drift.
Mean sea level	Average height of the sea surface over a 19-year period.
Mean high water (MHW)	The average of all high waters observed over a sufficiently long period.
Mean low water (MLW)	The average of all low waters observed over a sufficiently long period.
Met Office	UK Meteorological Office
Monitoring	Systematic recording over time
Nearshore	The zone that extends from the swash zone to the position marking the start of the offshore zone, typically to water depths of about 20 m.
Numerical modelling	Analysis of coastal processes using computational models.
Offshore	The zone beyond the nearshore zone where sediment motion induced by waves alone effectively ceases and where the influence of the seabed on wave action has become small in comparison with the effect of wind.
Overtopping	Water carried over the top of a coastal defence due to wave run-up exceeding the crest height.
Overwashing	The effect of waves overtopping a coastal defence, often carrying sediment landwards which is then lost to the beach system.
Physical modelling	The investigation of coastal processes using a scaled model.
Return period	A statistical measurement denoting the average probability of occurrence of a given event over time.
Rock armour	Wide-graded quarry stone normally bulk-placed as a protective layer to prevent erosion of the seabed and or other slopes by current and/or wave action.
Scour	Removal of underwater material by waves or currents, especially at the toe of a shore protection structure.

Term	Definition
Sea level change	The rise and fall of sea levels throughout time in response to global climate and local tectonic changes.
Seawall	Massive structure built along the shore to prevent erosion and damage by wave action.
Sediment	Particulate matter derived from rock, minerals or bioclastic debris.
Sediment grading	Distribution defined by nominal and extreme limits with regard to size or mass of individual sediment grains.
Sediment transport	The movement of a mass of sedimentary material by the forces of currents and waves. This can be either perpendicular to the shoreline (cross-shore) or parallel to the shoreline (longshore).
Significant wave height, H_s	The average height of the highest of one third of the waves in a given sea state.
Shoreline Management Plan (SMP)	An SMP provides a large-scale assessment of the risks associated with coastal processes and presents a policy framework to manage these risks to people and the developed, historic and natural environment in a sustainable manner.
Standard of protection (SoP)	The level of return period event which the defence is expected to withstand without experiencing significant failure.
Still water level (SWL)	The level that the sea surface would assume in the absence of wind and waves.
Storm surge	A rise in the sea surface on an open coast, resulting from a storm.
Sustainability (in coastal flood and erosion risk management)	The degree to which coastal flood and erosion risk management options avoid tying future generations into inflexible or expensive options for flood defence. This usually includes consideration of other defences and likely developments as well as processes within catchments. It will take account of long-term demand for non-renewable materials.
Swash	The area onshore of the surf zone where the breaking waves are projected up the foreshore.
Swash aligned	A coastline that is orientated parallel to prevailing incident wave fronts.
Swell waves	Remotely wind-generated waves (that is, waves that are generated away from the site). Swell characteristically exhibits a more regular and longer period and has longer crests than locally generated waves.
Tidal current	The movement of water associated with the rise and fall of the tides.
Tidal range	Vertical difference in high and low water level once decoupled from the water level residuals.

Term	Definition
Tide	Periodic rising and falling of large bodies of water resulting from the gravitational attraction of the moon and sun acting on the rotating earth.
Toe level	The level of the lowest part of a structure, generally forming the transition to the underlying ground.
Wave climate	Average condition of the waves at a given place over a period of years, as shown by height, period, direction and so on.
Wave direction	Direction from which a wave approaches.
Wave induced currents	The movement of water driven by breaking waves that create a current travelling in an alongshore direction.
Wave height	The vertical distance between the crest and the trough.
Wave hindcast	In wave prediction, the retrospective forecasting of waves using measured wind information.
Wave period	The time it takes for two successive crests (or troughs) to pass a given point.
Wave refraction	Process by which the direction of approach of a wave changes as it moves into shallow water.
Wave reflection	The part of an incident wave that is returned (reflected) seaward when a wave impinges on a beach, seawall or other reflecting surface.
Wave run-up/ run-down	The upper and lower levels reached by a wave on a beach or coastal structure, relative to still water level.
Wave transformation	Change in wave energy due to the action of physical processes.

Appendix: Comparative analysis summaries

This appendix contains summaries of each case study comparative analysis, providing an overview of the scheme and key findings regarding the differences or similarities between predicted and actual performance, and lessons that can be learned from that case study.

A separate project technical report provides, for those interested in the finer details, the full case study assessments.

A.1 Bournemouth

What will I find in the case study?

This is a beach scheme that has been actively managed for almost 40 years without any recourse to modelling. There have been regular nourishments to maintain the beach to design levels, but those design levels and the requirements for recharge are all developed solely upon analysis and interpretation of beach survey data. This example illustrates how this information can be used in this way and the importance of maintaining comprehensive records of beach management activities and beach responses.

Overview of scheme

Design

The beach has been monitored regularly since 1974 by means of surveying of beach profiles. During this time there have been 24 small- and large-scale beach replenishments along the frontage, with almost 2 million m^3 of sand. It is estimated that another approximately 3 million m^3 will be needed over the next 50 years to maintain the beach to a sufficient standard.

Losses amount to 1 million m^3 over 13 years (approximately 70,000 m^3 per year), with that sand going onto feed beaches further east.

The approach to design of beach management is based entirely on monitoring, observation and empirical relationships between the variables. No modelling has been conducted and no reference has been made to hydrodynamic conditions within the design process, although considerations have been given to wave climate observations in context with potential drift directions. Past performance data are used to project future losses of material. Crisis thresholds (in this case the minimum beach volume) are based upon the volume in 1987 when seawall failure occurred.

Renourishment has taken place in several phases with each project referred to as a 'Beach Improvement Scheme' (BIS), the latest being BIS4 which involved: placement of 1.1 million m^3 of dredged material in 2005-2006; another 800,000 m^3 in 2006-2007; and planned additions of approximately 70,000 m^3 to specific groyne bays in each of 2008, 2009 and 2010. The long-term plan makes provision for the next major recharge of 210,000 m^3 in 2015, with levels subsequently 'topped up' every 3–4 years to maintain the optimum beach.

Performance

Design beach cross-sections are determined empirically on the basis of previous schemes. In previous projects the design crest was set at or slightly above that likely to be reached by wave run-up. Consequently no waves overtopped the beach but the run-up formed a cliff, up to 2 m high, in the newly placed fill. This stood almost vertically for quite some time, forming a hazard to beach users, and eventually had to be bulldozed down.

Earlier approaches also included a single large-scale scheme with a 13-year cycle, with an acceptance of large-scale losses. However, it was seen that within that cycle the standard of service fell to a level below the crisis conditions.

Since implementation of BIS4, emergency works have not been necessary as the alarm thresholds have not been reached and top-ups have been conducted when the beach was above this threshold.

Additional points of note

The sediment particle size grading for the beach was nominally the same for both BIS2 (1974) and BIS3 (1988), but was different for BIS4 which incorporated a wider range of particle sizes along the frontage; this does not seem to have had any performance effect on the scheme.

Groynes were replaced during the 1980s and then again in 1995 to create a standard spacing, also reduced from previous spacing. Based on monitoring data, the groyne spacing appears to be too wide in places along the beach to minimise loss from some individual groyne bays. However, the length of the groynes appears to be suitable to retain sufficient beach material.

Assessment

Key findings

A formal beach management plan is not in place for the scheme. Beach management relies on the comprehensive monitoring programme in conjunction with empirical predictions to provide a decision support system for intervention.

The beach extends to approximately 100 m offshore, beyond which minimal change takes place. The monitoring includes regular bathymetric surveys and unusually provides a full picture of beach evolution including the submerged element of the profile.

Coupled with that, all of the observations are extremely well and comprehensively documented over a period of many years. This has been imperative for informing the ongoing effective management of the frontage.

There is an implicit assumption in the approach that wave climate is not changing significantly with time, since the design reflects the beach responses and performance of previous schemes since 1974. Interestingly, analysis of modelled pre- and post-construction data (as part of this study) indicates that those conditions post-scheme have been of similar intensity and frequency to those during earlier phases.

Beach response observations indicate that the volumetric changes to the beach have initially been as projections suggested. Experience from previous large-scale recharges has suggested that an accelerated rate of loss might be expected immediately following a recharge operation, as the beach seeks to establish an equilibrium position. Such a response is indeed evident following the second phase of the BIS4 scheme, when losses of 250,000 m^3 occurred within a period of six months. Subsequent losses have though occurred broadly in line with the projected rate of change, although the rate of loss has reduced since 2008 when the beach volume seems to have stabilised, and in the past two years seems to have actually increased. It is possible that this reflects the healthy supply of material that is available from beaches updrift at Poole, which was also recharged in 2005-2006 at the same time as the first phase of BIS4. Smaller interim recharges have had a more limited effect on the rate of loss. Overall, the pattern of change appears to be better than the empirically derived projected losses might suggest. This is perhaps a function of more pessimistic design stage projections of losses, relative to earlier schemes.

The BIS4 scheme was designed with a beach crest level of 2.0 mOD, considerably lower than the natural beach crest level of about 3.0 mOD. This meant that the sea immediately overtopped the newly placed material and pushed up a storm beach crest, depositing it in a very ‘natural’ profile, much better than could be achieved by bulldozing. This approach has also avoided cliffing of the beach, which had occurred following previous recharges built to higher elevations.

Lessons

The lessons that can be drawn from this case study which may be of benefit to further schemes include the following.

- It is possible to successfully manage a beach scheme over a long period of time without requiring modelling. This is only possible because of knowledge built up over a considerable period of time, the maintenance of comprehensive records of activities and beach response, and the ongoing application of expertise to analyse and interpret that information effectively.
- Whether some modelling of beach behaviour might have led to a more cost-effective or less effective scheme is impossible to say. However, limits on the ability to use past performance solely to predict future requirements will become increasingly difficult if accelerated climate change starts to alter the wave conditions from those experienced in the past.
- Large-scale renourishments are more likely to experience higher losses, with these occurring early on in the life of the scheme. This needs to be accounted for when undertaking larger campaigns, although needs to be balanced against the potential disadvantages (for example, economic or disruption) of more regular lower volume nourishment activities.
- Constructing a beach to a lower than storm level and allowing nature to build the upper beach profile can be advantageous to avoid cliffing and improve public safety.

A.2 Folkestone

What will I find in the case study?

This is an example of a scheme developed through the application of established empirical plan shape design methods to create stable shingle embayments between artificial rock headlands. This example illustrates the high dependency of the success of the design on detailed wave modelling of the inshore wave climate and considerable discussion on this point can be found in here.

Overview of scheme

Design

The Hythe and Folkestone scheme comprised of three artificial headlands constructed of rock, with 150,000 m^3 of shingle beach recharge between the structures, forming two 'stable' bays.

One of the principle influences over the design method and scheme selection was the identification of the strong uni-directional focus of waves in this region. This presented the ideal conditions for static equilibrium bays. These were designed using the empirical methods of Hsu and Silvester, with the procedure for testing the stability of a given bay based on the fit of the log-spiral shape to the beach planform. The logarithmic spiral shape used to describe the equilibrium shoreline forms as a function of interaction between the angle of wave approach and the controlling headlands.

Good definition of the wave climate was therefore critical, so numerical modelling of wave transformations from offshore to inshore was carried out and the bay shape formed for different configurations of control structures was assessed by modelling the wave fronts produced by the diffraction and refraction effects of the structures.

Performance

It was not anticipated that any regular beach management or renourishment would be required within the bays and this has been the case in the eight years since completion of the scheme in 2004, with the beaches having remained stable with the only significant reduction in volume being an initial 6% volume loss, the majority of which occurred within the first three months following completion.

This corresponds with the predictions made of initial volume losses resulting from the wash-out of fines from the renourishment material, which were based upon other local experience. A loss of volume of 5% of the initial renourishment was estimated to occur within a year of the scheme completion and the actual recharge was increased by this amount to compensate.

The crests of the beaches within the two bays were placed exactly to the theoretical planform. While observations show that the orientation of the two bays fluctuate depending on the incident wave direction, this fluctuation is limited to about $\pm 2°$.

Additional points of note

While a beach plan shape model was used elsewhere along the adjacent frontage to optimise the location and length of groynes, it was not used to predict planform formation and beach stability along this frontage. This was because beach plan shape models were not considered capable of replicating the strong diffraction influence of the rock headlands used to form the static equilibrium (crenulated) bays.

A grading envelope was specified for the dredged material used for beach renourishment to ensure that the correct balance of coarse and fine material was delivered to site. The specified D_{50} value of this grading was 15 mm and was placed to the specified planform to an initial profile of 1 in 8. Although this formed a slightly steeper beach than that naturally occurring on the frontage, this was deliberate to ensure that the extents of the beach profile remained within the envelope bounded by the rock control structures.

Assessment

Key findings

The key parameter in terms of the performance of the beaches is the average wave direction. From the pre-construction wave modelling, it was determined that the inshore wave climate in this location was uni-directional. This was one of the most important factors influencing the design and approach adopted.

When the beach planform predicted by the Silvester log-spiral method is compared with that predicted by the mathematical wave model, it can be seen that there is relatively good agreement between the crest line positions predicted by the two methods. Observations show that actual performance is in good agreement with the variations predicted by the mathematical models during design of the scheme.

Assessment of the predicted and actual scheme performance highlights the performance of the two bays as very similar, even though the distance between the control structures of each bay is very different. This suggests that the application of this method for predicting the planform of static equilibrium bays is not affected by the size of the bay in relation to the predominant wave climate.

In addition, the tightness of the theoretical curve at the western end of the bay is not reproduced in practice. This is considered to be most likely due to the transmission of wave energy over and through the rock headland structures, which has the effect of transporting material eastwards along the bay, a feature that would not be seen in natural rocky outcrops.

According to the theory, the curve at the downdrift end of the bay should be aligned to face the averaged wave energy direction. This has occurred, suggesting that the prediction of the inshore wave climate taken from the mathematical model was correct. The fact that the bays have compensated for the loss in volume only at the downdrift ends may therefore be a function of the location of the downdrift control points.

Lessons

The application of crenulate bay theory as an empirical model to design stable beaches has been shown able to deliver a successful and sustainable solution that reflects naturally functioning shoreline features. Good definition of inshore wave direction is critical to that success.

Two other lessons can be learned from the observations of the beaches at Folkestone. Firstly, if a similar approach is adopted elsewhere and the headland control structures are to be constructed from rock armour, then account should be taken of the transmission of wave energy over and through the structures which may affect the plan form locally. Secondly, the performance of the downdrift control points is susceptible to the structure form. Consequently care should be taken when deriving these points and when designing rock structures to act as control structures.

A.3 Hurst Spit

What will I find in the case study?

Details of a scheme to stabilise a shingle barrier beach, not backed by other structures, where management of its position and width/elevation are critical design factors. This example contains a comprehensive description of 3D physical modelling, used in conjunction with numerical modelling, to understand the processes and behavioural characteristics of the beach to provide an appropriate design. Particular detail is provided on the wave characteristics at the site and how these affect beach response and model predictions. Furthermore, this illustrates the use of monitoring in combination with understanding drawn from the extensive modelling to be able to confidently adapt the beach management regime.

Overview of scheme

Design

Hurst Spit is a 2.5 km long barrier beach, the plan location of which can be stabilised only if green water overtopping of the beach, which results in crest roll back, is prevented. The stabilisation scheme involved adding 300,000 m^3 of shingle recharge to the barrier beach placed at a varying crest level. Other features of the scheme included a rock revetment towards the eastern end of the beach and a nearshore rock breakwater at the western end. Planned maintenance work was limited to recycling of material and bypassing of the breakwater in years 1–10. The first planned interim recharge was scheduled for year 10, when an estimated 100,000 m^3 of shingle would be required, followed by similar recharges at 15-year intervals until year 40.

The scheme design was based primarily on 3D mobile bed physical modelling, supported by numerical modelling of sediment transport. The modelling included the following elements:

- mathematical modelling of the nearshore wave climate
- validation of the physical model methodology for shingle barrier beaches
- physical modelling of four overlapping segments of Hurst Spit at a scale of 1:40
- numerical modelling of sediment transport, interactive with the physical model

Performance

Following construction in 1996 the beach has been monitored by topographic and hydrographic surveys, in parallel with wave and tidal measurements. Beach response has been close to that predicted for the storm events. Threshold levels have been maintained in accordance with the original design criteria, although it would appear that the standard of service of the beach is significantly lower than the original design conditions would suggest.

The planform developed following construction is remarkably similar to that developed during physical model testing. It has performed as suggested by the physical model tests during a post-construction monitoring period of more than 16 years.

Longshore transport calculations conducted at the design stage suggested faster transport rates than have actually occurred. Annual losses of 16,000 m^3 per year were predicted but have actually only averaged 7,500 m^3 per year, meaning that the first interim recharge (10 years) has not been required. Allowance was made within the design programme for annual maintenance for the first 10 years with an annual average of 5,000 m^3 of recycling. The required frequency for maintenance has been less frequent than that, with no maintenance at all conducted in some years, although the total volume of recycling is close, equating to an average of 4,500 m^3 per year.

Additional points of note

Measured wave conditions since scheme implementation have proven to be significantly different from the modelled wave climate. The design 100-year return period significant wave height has been exceeded on numerous occasions; wave period measurements are more widely scattered than modelled, but the measured periods are typically about 20% lower than models indicate; and a high frequency of storm events are represented by wave conditions with bimodal (period) characteristics.

Although the as-built construction geometry at this site was very close to that modelled; the main difference relates to the grain size distributions of the modelled and the actual recharge material placed, which included a sand content of about 20%. This will not have been accounted for in the modelling.

Extreme water level design data was derived from limited short-term deployments of tide gauges. The lack of certainty of design water levels presented a weakness in the design process.

Assessment

Key findings

Overall the scheme has performed generally better than might be expected despite wave conditions being significantly more severe than anticipated at the design phase. Observations do though demonstrate some differences between actual and expected beach responses. Many of these differences are interlinked and in this instance the under and over design elements seem to have cancelled each other out; this is attributed to good luck rather than adequate science.

Plan shape evolution has been broadly similar to that suggested by the physical modelling process and the breakwater has provided the expected stabilising effect as a headland structure. The longshore variability of sediment transport rate has matched that anticipated at the design stage, although sediment transport rates have been generally lower than predicted by numerical models. Consequently longshore losses from the system have been lower than predicted in the design. This may reflect the fact that moderate measured wave conditions are generally less severe than modelled conditions.

While the measured wave conditions have been somewhat different to those expected, cross-shore responses have been broadly similar to those modelled. Applications of empirical models of profile response and barrier breaching have been verified at full scale by reference to measured wave conditions. Where conditions have been characterised by similar conditions to those developed in the physical model based empirical frameworks, results have been comparable.

The implications of differences in wave climate observations though suggest that lower run-up might be expected under most conditions, since the modelled wave period appears to have been overpredicted. Many conditions observed have been outside of the range of the empirical frameworks. The implication is that wave run-up should also be lower than modelled and that the as-constructed crest might be higher than is optimal, resulting in a more reflective beach face; this has generally been the case. This is countered however by the impact of bimodal conditions, which were not considered in the design.

Despite the fact that the beach has remained in good condition, overwashing of the crest has occurred on a number of occasions. Wave climate conditions associated with these events were characterised by bimodal spectra on each occasion; a significant proportion of the energy component (20–40%) has typically been in the swell energy range of frequencies.

Cross-shore profile responses are not well described by models for bimodal wave period conditions. The models generally underpredict wave run-up and crest cut back in such conditions. While these observations are not conclusive, it appears that the threshold curves are not valid for prediction of overwashing under bimodal conditions. Current design guidance does not provide an obvious means of dealing with this design variable, apart from site-specific physical model testing.

Although the physical model was designed with material with no sand content, this does not appear to have an adverse effect on scheme performance. Beach slopes differ from those modelled, however, and the lower beach slopes are generally flatter than modelling of shingle with no sand fraction might suggest. Physical modelling of the beach uses lightweight materials (crushed anthracite) designed to simulate the hydraulic performance of shingle. The model sediment however was scaled to be representative of a shingle grading with a D_{50} of 16 mm, but with an effective cut off of material below a grain size of about 6 mm. This is a standard modelling practice, since mixed sediments cannot be modelled effectively at the required scale for 3D wave basin modelling. There would be a reasonable expectation therefore that the profile response of the actual beach and the model would differ, since a mixture of sand and shingle will have lower permeability so might develop a flatter slope and with a lower crest than that seen in a model.

Lessons

Design wave climates should include, as a minimum, several years of measured wave data to replace or complement numerical hindcasts. Since 2008, the Met Office wave model has been superseded by WAVEWATCH III; this model appears to reproduce wave heights more reliably, with the bias evident in the Met Office model being removed. To provide design conditions, appropriately long-term hindcasts ought to be based on the most recent model. This approach will improve the ability to model sediment transport more accurately, since this is strongly dependent on wave height data.

However, WAVEWATCH III does not appear to reproduce wave periods more reliably than the Met Office model, although it does provide a better frequency resolution and less scatter. Therefore where wave run-up or overtopping is significant, model wave data should be validated against measured data and adjusted to reflect the measured wave periods.

Experience at the Hurst Spit site suggests that regularly occurring bimodal conditions may do more damage than extreme events determined using conventional extremes analysis methods. Assessments of wave climate need to examine the outputs of models and measured data carefully to determine whether bimodal conditions occur at the site. Site-specific tests should be conducted which reflect such conditions to assess the increased risk of overwashing. A probability distribution of bimodal events should be produced to allow assessment of the risks of these conditions.

Overwashing is underpredicted by the breach prediction model in bimodal wave conditions, but performs well when conditions lie within the limits of the original parametric framework. Adjustments to the empirical framework have not been achieved for bimodal conditions; this requires a more systematic approach to determining the effect of bimodal conditions. Using standard bulk statistic period variables, the empirical framework will currently underpredict the possibility of overwashing. Validation of the predictive curves for overwashing provides confidence in this assessment approach for the range of conditions tested. Extensions to the framework for steeper wave conditions may be applicable elsewhere.

A structured approach to monitoring and data analysis can provide a timely and detailed assessment of scheme performance to enable recalculation of the next interim recharge, with potential associated cost savings, and provide confidence in future projections. At Hurst Spit the monitoring has had a major impact on management of the beach system. It can demonstrate clear differences by comparison with modelled expectations and provide the basis for modification of maintenance and long-term planning requirements. Monitoring is particularly valuable for the purposes of evaluation of threshold damage levels and for long-term planning of interim recharge requirements.

A.4 Lincshore (Mablethorpe to Skegness)

What will I find in the case study?

This is an example of a large-scale intensively managed open beach scheme. This sand recharge scheme covering over 20 km of frontage has been built up and maintained by annual renourishment campaigns for the last two decades. Wide-ranging detailed model studies were undertaken initially to understand coastal processes, develop the design and further evolve the scheme. The scheme now benefits from a comprehensive long-term and highly detailed record of beach management activities and beach response, which forms the primary tool used for recent and future management decision-making.

Overview of scheme

Design

The scheme was designed to replace a denuded beach where the presence of seawalls was exacerbating lowering of beach levels, with significant exposure and ongoing loss of the underlying clay layer.

The original 1991 strategy was for a capital recharge of approximately 7.6 million m^3, which was undertaken between 1994 and 1999, followed by annual recharge campaigns to replace annual losses. The latter was initially expected to limited recharge or recycling in the first few years (approximately 70,000 m^3 per year) and then from 2003 between approximately 330,000 m^3 and 370,000 m^3 per year on average.

This strategy has been subject to an approximately five-yearly regular review process to continually re-evaluate the overall strategy and re-assess the predicted recharge quantities over the coming periods (this is in addition to annual assessment and volume adjustments which reflect inter-annual variability in conditions). Those reviews took place in 1998, 2003 and 2009. These have resulted in some changes to planned annual nourishment and some modification to the design beach profile (see performance).

There have been a number of studies using modelling, surveys and data analysis to assess conditions and scheme requirements to inform the original strategy and subsequent reviews. In addition to detailed analyses of the long-term survey records in 2003 and 2008 (beach survey data here goes back to 1959), there has been extensive modelling and analysis of coastal processes and beach performance in 1991, 1998, 2004 and 2008, which has included:

- wave transformation modelling
- numerical cross-shore modelling of storm beach profile response including sand movement and clay down-cutting
- sediment transport modelling (longshore transport, cross-shore transport and coastline evolution)
- surf zone modelling to evaluate cross-shore losses of recharge
- sediment transport and shoreline evolution with one-line models

Underpinned by the above understanding, the specific requirements for each annual beach nourishment campaign are now largely directed by analysis of the annual post-winter beach surveys.

Performance

The first phase of the strategy, competed in August 1995, involved placing the first 1.5 million m^3 of beach nourishment over a 2 km section. Construction of the second phase, over a 17 km frontage, started in September 1995 and was completed in September 1998, placing about 6 million m^3 of sand. All material used for the nourishment has been dredged from offshore commercially licensed sources.

Early analysis of the monitoring (1998) after the initial capital recharge found that generally the beaches had performed well, with the crest berm remaining stable in the majority of locations. Large volumes of sand had been lost from the promontories, as predicted. The overall changes in sediment volumes were quite small (7% of original volume). However, there had been erosion on the upper slope and accretion on the lower slope, such that the placed 1:25 single slope had typically changed to a steeper upper slope and flatter lower slope. Analysis indicated that the coarser sediment was tending to remain on the upper beaches while the finer fraction was migrating seawards, possibly accreting in the intertidal zone. The renourishment placement profile was subsequently adjusted to a 1:15 slope. The 1998 strategy review also reused the original models to calculate longshore sediment transport. There has been apparently good agreement between the modelling and survey results since 1994, and this was used to justify the calculated transport rates for the prediction of required renourishment works.

The subsequent phases were to renourish the frontage with dredged material to replace the losses due to natural processes. However, with the change to beach slope, the projected annual losses from 2004 onwards were amended to approximately 155,000 m^3 per year (less than half that previously estimated) up to 2048, but following another renourishment of about 1.6 million m^3 over the subsequent four years. Funding constraints, however, resulted in the placement of smaller volumes over a six-year period, a consequence of which was that the standard of protection fell below the 1:200 target in some areas.

At the next strategy review (2003-2004), the expected future annual requirement was increased back to 320,000 m^3 per year following the placement of larger quantities totalling 2.4 million m^3 in 2005-2007 to address the drop in standard of protection during phase 3m, plus a decision to provide a wider design crest berm width. Maintenance of the beaches following this still though required nourishment volumes of around 400,000 m^3 in 2008 and 500,000 m^3 in 2009.

The analysis undertaken for the next strategy performance review (2008) primarily focused on beach performance data rather than any further sediment transport modelling, but also found that the Met Office hindcast offshore wave data had previously underestimated storm waves, particularly for storms from the north. This analysis concluded that the long-term project renourishment requirements should be increased to an average of 340,000 m^3 per year, initially with increases in future to counteract climate change to 350,000 m^3 per year in 2020 and to 380,000 m^3 per year from 2060, that is, not dissimilar from those in the initial strategy albeit some other factors such as overall beach slope and volume had since altered.

The 2008 performance review of the strategy also used beach volume analysis to demonstrate that there are four main areas of erosion or ‘hot spots’ along the frontage. The analysis also indicated that, while the strategy recharge campaigns at the hot spots had been sufficient to keep pace with beach losses, there have been periods when beach profiles can revert back to less than the design standard of 1 in 200 years. In effect, this is what triggers the subsequent recharge campaign as a key driver for the scheme is the need to stabilise the beaches to prevent down-cutting of the clay substrate below the sand and gravel beaches in order to sustain the hard defences at the back of the beaches into the long term.

Additional points of note

The natural sediment on this beach was reported to have a typical D_{50} of approximately 0.25 mm. Modelling to inform design quantities and profile considered various sand sizes (0.25–0.65 mm). Accounting for initial losses and design beach slopes, options for phase 2 nourishment quantities (1995-1998) varied from over 16 million m^3 for 0.25 mm sand to under 5 million m^3 for 0.65 mm sand. The cross-shore modelling of 0.25 mm sediment (1995) also indicated that around 500,000 m^3 could be stripped from the upper beach of the project frontage during a single storm. This resulted in the selection of coarser 0.6 mm D_{50} sediment in the design to reduce offshore losses.

Assessment

Key findings

The cumulative volume of sand placed on the beaches to date has been approximately 30% more than originally expected, primarily as a consequence of a need to place more than expected between 1998 and 2007 to build the beach up to (modified) design levels and since then placing on average 500,000 m^3 per year to maintain those levels.

It should be noted that the initial 1991 modelling of longshore transport had to draw certain conclusions as the basis for the initial recharge scheme and subsequent expectations regarding renourishment. However, there was at that time no nearshore wave data available to validate the wave models and no sediment transport data available to calibrate or verify the sediment transport calculations. The underestimation of annual losses and hence recharge requirements may be at least partly due to this lack of calibration data for the sediment transport models.

Analysis of wave monitoring data since collected offshore and at nearshore points along the strategy frontage indicate that the Met Office offshore wave data later used for the 2003 strategy review may have also underestimated wave conditions, in particular not accounting for larger storms from the north. This means that the sediment transport rates calculated then may have been too low. The extent of losses since may therefore be partly due to the greater than anticipated alongshore wave energies driving more material outside the recharge areas and into the more stable accretion areas.

It is also possible that offshore losses may have subsequently occurred which were underestimated in the past, particularly given that the beach profile response has differed from that originally expected. It is possible that cross-shore transport was not fully accounted for; studies seem to indicate the importance of cross-shore sediment exchange, but it is not clear how fully this has been incorporated into the modelling and quantification of future requirements.

The adopted approach to beach management of now using actual survey data alongside model predictions to determine actual annual recharge requirements has proved necessary and indeed successful. The flexible approach of using measured data to update and improve modelled estimates has allowed the beach management plan and future estimates to be updated as the scheme has progressed.

Lessons

The lessons that can be drawn from this study which may of benefit to further schemes include the following.

- The modelling should consider both the native (pre-erosion) sediment and options for available sediment from recharge sources under consideration.

- Met Office model wave data may underestimate actual conditions and therefore adjustment or calibration of the data should be considered before use.
- When uncalibrated models are used to derive long-term requirements for beach recharge, suitable contingency factors should be included in deriving final estimates or the models should be revisited as better data become available.
- Regular review of the performance and updating of the beach management plan as additional data become available is important, especially for large schemes where beach response is highly volatile.
- As longer term monitoring datasets become available, they can provide a more reliable means to predict and plan future beach performance. Ahead of those data existing, comprehensive and wide ranging modelling can be critical for assessing and selecting the most appropriate beach management approach.
- The objectives of all modelling exercises and how they relate to one another need to be clearly documented. Furthermore, the links between the model findings and subsequent design/implementation need to be explicitly documented.

A.5 Littlestone

What will I find in the case study?

An example of comprehensive modelling of an open shingle beach scheme, including plan shape and cross-shore, but where differences in actual environmental conditions from those expected and used to drive those models, compounded with a change in beach material size from that modelled, resulted in a quite different beach response to that expected.

Overview of scheme

Design

The scheme design included a capital beach nourishment of approximately 260,000 m^3 of shingle (sourced from an offshore licensed dredging area) and the construction of a terminal rock groyne at the northern boundary of the frontage, with an estimated 5,000 m^3 of accumulated shingle material recycled annually from there to the southern part of the frontage.

Numerical modelling was undertaken to provide waves and water levels for scheme options appraisal and design. The numerical modelling included joint probability analysis of wave and water level extremes, tidal current modelling, wave overtopping, beach plan shape and alongshore drift modelling, and beach profile cross-shore storm beach response modelling.

Performance

Following completion of the scheme in 2004 two key issues not identified in the modelling were readily apparent. The first was that the shingle was moving in a southerly direction (opposite to the predicted direction), building up and creating operational issues for two slipways and an outfall. The second was the drift of material beyond the southern boundary of the scheme where environmental designations precluded its recovery for recycling, with this loss meaning an overall reduction in beach volume and thus standard of protection afforded by the beach.

Further problems were also experienced with recovery of material from the terminal groyne, with the geometry and permeability of that structure meaning material transported in that direction was not being retained to the extent predicted. There are two elements here. First is that the permeability of the groyne enabled the beach material to flow more freely through the structure than was perhaps expected in the modelling. The second is the actual geometry of this structure allows more material to bypass it than it would appear was included for in the modelling. However, it is not clear whether the modelling informed the geometry or not.

Actual recycling operations in 2005 and between 2009 and 2012 required between 3,000 m^3 and 21,800 m^3 of mixed sand and shingle taken from locations along the southern part the frontage and deposited along the foreshore further north.

Additional points of note

While the general intention of the capital nourishment in 2003 was to nourish the beach with sediment of a similar size and grading to that which already existed on the site, shingle actually placed on the beach had a D_{50} value significantly lower (12 mm or less) than the material that would be expected to be naturally found on this frontage (15–17 mm) and was much wider graded than would normally be expected. The actual size used for modelling is not known, but it might be assumed to have been based on the native beach material unless the planned nourishment source was already known and had been sampled.

Assessment

Key findings

In summary the two main reasons for the difference between expected performance and actual performance are as follows.

- The smaller and wider graded sediment used for beach renourishment compared with the assumed values used for the sediment transport modelling resulted in different beach movement characteristics.
- The frontage is sensitive to wave direction and the modelled wave dataset would not seem to be representative of the actual conditions that have been experienced post-construction. The greater occurrence of larger wave heights prior to scheme construction indicates that the sediment transport modelling may have overestimated sediment transport rates post-construction.

The orientation of this site and local wave climate means there is potential for beach material to be transported in either direction. The results of the numerical modelling undertaken as part of the detailed design for the scheme show for the analysis period (1971-1998) that more waves would come from the sector driving net sediment transport northward rather than southward transport, and comparison with wave rider buoy data would offer a similar conclusion.

However, further analysis based on UK Met Office modelled data between 1989 and 2011 show that there have been very few large storm events post-scheme and this trend becomes dramatically apparent when compared to the first half of the wave record (1988-2001) where storm events occurred much more frequently and with significantly greater peak wave heights. Directional data for these storm events are not known, although anecdotal evidence suggests that many of the larger events experienced before the completion of the scheme were southerly storms. These would have contributed significantly towards the northerly sediment transport component. The reduction in large southerly storm events may well be a contributing factor to the net southerly transport experienced post-scheme.

The as-placed shingle had a significantly lower D_{50} value and had a significantly wider grading than assumed in the modelling. The consequence of this is that the smaller material within the newly placed beach is mobilised under lower wave energy conditions. This in turn means that the point along the frontage at which shingle ceased to be influenced by the wave action is further south. The introduction of smaller sized sediment increased its mobility, while the overall increase in material volume along the frontage also resulted in an increase in the surface area of material exposed to wave action. Therefore the rate of southerly sediment transport in the vicinity of the slipway towards the southern end of the site increased.

During high energy northerly events, a significant volume of material is transported south along the frontage. As there have been no significant westerly storms in the period since the nourishment to offset the southerly movement of shingle, material built up against the slipway, which acted as a groyne structure resulting in accretion. Given the shallower water at the southern end of the study frontage, inshore wave energy is less than that on the slightly deeper and more exposed northern half of the frontage. Consequently, material that has been moved onto the southern half of the frontage is less likely to be moved back in a northerly direction.

Lessons

The scheme design was based on the premise that the net sediment transport direction was south–north and therefore the terminal groyne at the northern boundary would prevent losses from the frontage. Actual sediment transport regime along this frontage is more complex. While the net transport direction is important in general terms, what is critical is the fact that the consequences of both the southerly and northerly components of this regime result in a different outcome to that which was predicted using the net transport direction alone.

Lessons to take forward from this are as follows.

- For frontages that are potentially sensitive to changes in sediment transport direction, apply sensitivity tests to the directional wave data used in the model. This can provide an envelope of outcomes from which beach management options and the potential extent of variability/flexibility can be better determined.
- In considering sensitivity, consider also other schemes being examined in the vicinity (for example, wave analysis for the Folkestone scheme was undertaken at a similar time but it is not known whether there was any cross-referencing).
- When modelling sediment transport using a single sized (D_{50}) value, it is necessary to understand that most as-dredged material will be relatively wide-graded. This may result in a natural sorting of material with finer sediments being transported under more frequent, but lower energy events and larger sediments only being transported under higher wave energy events. The behaviour of mixed sand/shingle beaches is complex and not always well replicated by numerical sediment transport models, but again scenario testing considering a range of sediment sizes can help to better inform the designer of potential variability in the outcome and build that into the management planning.
- Consequently, there needs to be an element of engineering judgement applied to the results of the model. Validation of predictions is not always possible but reference to site inspections, monitoring data and local knowledge is important to consider in providing confidence or raising questions regarding beach response.

A.6 Llandudno North Shore

What will I find in the case study?

An open beach scheme with phased works, with design supported by a range of different modelling approaches including waves and sediment transport rates, followed by physical modelling to examine different configurations for the scheme. This example highlights the implications of changes between what was modelled and what is built, and the limitations of modelling only part of an interactive and interdependent coastal system.

Overview of scheme

Design

The scheme was implemented in two phases. The first phase in 1996-1997 comprised the importation of approximately 60,000 tonnes of material to recharge the beach levels in front of the defences, as well as carrying out repair works including a low level terminal groyne at the eastern boundary of the recharge. A terminal rock groyne was also installed at the western limit of the scheme to prevent westerly drift of the imported beach material into the adjacent section.

The second phase of the works, constructed in 2000, involved extension of the recharge westerly for a further 460 m importing a further 20,000 tonnes of recharge. The existing slipway towards the western end of the frontage was enlarged, providing a permanent terminal groyne and the temporary rock structure was removed at this time.

Initial scheme study comprised wave refraction modelling to provide inshore wave conditions and empirically based assessments to define preliminary details (cross-shore profile, sediment transport calculations). This was followed by development of a 3D physical model to examine various beach recharge/control structure arrangements (1:70 scale). Physical modelling examined annual average and a range of extreme events from two different wave directions.

Annual drift rates predicted due to normal conditions varied between 200 and 20,000 m^3 per year dependent on location with the higher values anticipated to occur over a short length (approximately 250 m) mid-way along the phase 2 frontage. Drift rate factors under storm conditions could potentially increase rates by 2–4 fold and 5–12 fold for 1 in 10 year and 1 in 50 year storm conditions, respectively. The modelling identified the need for recycling material from east to west following storm conditions and more regularly once alarm conditions (minimum crest level) were reached.

Performance

Beach management since the scheme was implemented has been fourfold:

- retrieval of material moved longshore (within the length recharded)
- retrieval of material moved on/offshore
- retrieval of material thrown up onto promenade
- re-profiling where beach has steepened due to storm action

Following completion of the first phase, approximately 40,000 m^3 of material was lost from the frontage, notwithstanding that 12,500 m^3 was added as part of the second phase of works in 2000. In March 2010 approximately 3,500 tonnes of additional cobble was imported and placed across the phase 2 length.

Based on the results of the monitoring surveys up to and including 2008, the frontage has been losing material at a rate of nearly 3,000 m^3 per year.

Generally material is lost from the upper sections of the beach and transported easterly along the frontage or material is drawn offshore, some of it into the areas below low water mark. Cyclical behaviour is observed between surveys with losses followed by gains, indicating that material that is drawn offshore during storms can be returned but generally only to the lower sections of the foreshore. Material can move bi-directionally and, prior to the first phase recharge, the frontage to the east lost approximately 40,000 m^3, primarily as a result of a north easterly storm in 1996.

Under normal conditions the beach profile is generally maintained, but under storm conditions the profile deforms, as predicted by the Powell model. However, storms also cause complete destruction of the crest and beach drawdown with material being thrown up onto the promenade.

The permanent terminal groyne at the eastern end of the recharged section of frontage appears to providing a beach retention function by controlling upper beach drift at this end. However, the gains on the eastern side indicate that material is bypassing the structure lower down the beach and feeding the frontage to the east.

Additional points of note

The D_{50} of material used in the scheme was coarser than that used in the modelling. There was a requirement for material to match or be coarser than existing sand/shingle mix for performance and environmental reasons: modelled sediment was shingle (D_{50} = 40 mm) whereas sediment in final scheme was coarse shingle/cobble (D_{50} = 60–80 mm).

Assessment

Key findings

The losses identified have been within the range of drift rates predicted by the modelling undertaken. However, it is likely that the coarser material used in the scheme compared with that modelled will have contributed to drift rates and losses being lower than would otherwise have been the case.

Potential reasons for differences between the modelled and actual performance have been identified as follows:

- different wave climate (directional and height/period) – actual post-scheme wave climates **will not** be the same as those used in the modelling
- different sediment size used in the works compared with that used in the model
- modelling did not identify on\offshore movement and did not consider beach performance on a whole recharge frontage or even bay wide scale

Furthermore, the modelling of the scheme did not consider:

- two-phased approach to implementation
- impacts of permanent and temporary terminal groynes
- beach behaviour across the whole of the recharged frontage or the whole bay

Overall, the gross and nett movement of sediment that has occurred following scheme implementation has been within the limits identified by the model, although no material has to date been recycled from the east end of the frontage. The model also identified the phase 2 length as being an area where the greatest beach depletion would occur, which has been the case. The use of physical rather than numerical modelling to determine complex hydrodynamic interactions has been important in this regard, notwithstanding that cross-shore interaction was not accurately replicated.

Lessons

The key lessons to be learnt from this scheme are as follows.

- Modelling should be considered as one of a range of tools to inform scheme definition for beach recharge schemes.
- A thorough understanding of process behaviour and likely scheme behaviour backed up by empirical calculation and judgement are essential.
- It is important to identify appropriate boundary conditions for modelling and post-scheme evaluation.
- Where appropriate, modelling may need to consider behaviour over a wider basis than just potential scheme limits, which was not the case here.
- If possible, modelling should consider a range of potential sediment sizes.
- As far as possible, modelling should seek to replicate potential future conditions or ranges of conditions against which actual scheme performance can be assessed.
- Ideally, modelling should provide sufficient information that can, in association with post-scheme monitoring, provide the basis for scheme performance evaluation and be used to inform future beach management requirements.

A.7 Pett (Cliff End to Rye Harbour)

What will I find in the case study?

This is a comprehensive example of 1D modelling of alongshore shingle movement for an intensive recycling scheme along a groyned beach frontage. Considerable detail is provided on the calibration and application of the plan shape model. Discussion is also provided on the use of cross-shore beach models used in combination with this to design the groyne lengths and spacing. This is also an example of where the management regime was not able to adhere to the planned programme of works, but information gained from modelling still proved useful to understand ongoing beach behaviour and inform the management response.

Overview of scheme

Design

The design involved the staged replacement of a redundant timber groyne field, intensive recycling of a shingle upper beach over eight years using native material, to be followed by annual recycling of 30,000–50,000 m^3 per year to maintain the beach. The shingle source for recycling was from an accumulation at the downdrift end of the 8 km frontage.

Design of the scheme, which considered a wide range of groyne and recycling combinations, included:

- wave transformation modelling
- one-line beach plan shape modelling
- numerical and empirical cross-shore modelling of sand foreshore and shingle upper beach profile
- calculation from above models of alongshore sediment transport rates

The presence of a candidate Special Area of Conservation (cSAC) and Special Protection Area (SPA) in the area where material accumulated had a significant influence on the final design of the scheme. Originally, the intention was for a capital scheme that would be completed in a 12-month period to provide the required standard of protection. However, mitigation measures necessary to minimise the environmental impact of the scheme resulted in the scheme construction period being extended over eight years to minimise the impact of the extraction operation. It was, however, recognised that implementation would need to flexible to take account of the availability of shingle from the extraction pocket which could vary considerably year on year.

Performance

The scheme commenced in 2003-2004 with the plan to extract and place 90,000 m^3 of shingle. However, only 30,000 m^3 of recycling was undertaken, noted to be ‘due to circumstances beyond the Environment Agency’s control’. Subsequent recycling continued below the programmed amount (50,000–60,000m^3 per year) and, after eight years, the total shingle recycling that had taken place was 207,000 m^3 less than planned.

The pattern of recycling also differed from year 5 onward, with deposition taking place further updrift than planned; a reactive response to areas of localised crest width reduction, rather than planned recycling set out in the schedule of works. There was also a need for additional recycling, not originally planned for, at the westernmost stretch of the frontage and it was anticipated that there would need to be an ongoing beach management commitment at this location in the future.

Of the 31 new groynes planned in year 2, only 28 of those went in during years 2 and 3. By year 4 there had been erosion of the beach to the east of these which prompted the construction of the further groynes in year 6. Since construction of these there has been no further problem in that area, no evidence of scour downdrift and the beach has performed well and as designed.

Prior to the construction of groynes at the eastern end of the ‘Actively Managed’ frontage, there were problems of shingle loss and beach narrowing. Since construction of groynes in year 5 (a year later than planned), however, monitoring indicates that this section of beach has performing as predicted.

The latest beach monitoring report concluded that, with the exception of the western end, the required standard of protection has now been achieved and concludes that the standard of protection is improving year on year.

Given the significant difference between the proposed recycling and the actual recycling volumes, the beach has performed better than may have been anticipated.

Additional points of note

There was a four-year period between modelling for the scheme design and actual commencement on site. It is not known to what extent the condition of the beach had altered in that period, or whether a longer period of wave record may have resulted in further refinement of the design.

The constraints on recovery of material imposed by environmental designations required an unusual feature in the form of a ‘pocket’ to be recreated at the downdrift end of the frontage to allow extraction of shingle for recycling. Implementation of the scheme was therefore also dependent upon the rate of refilling of this pocket, for which there was a level of uncertainty; modelling using data over a seven-year period demonstrated that variability in annual transport rates could see this range from 30,000 m^3 to 73,000 m^3 per year.

Assessment

Key findings

Model performance

Design of the scheme involved extensive modelling and a large number of options were investigated, partly due to changes in scheme design necessary as a result of the environmental constraints on extraction. The modelling files indicate that much care was taken to replicate the real-life situation as accurately as possible, although it was acknowledged that it was not possible to take into account the reactive nature of recycling.

The 2011 beach monitoring report calculated that, from beach profile analysis, approximately 30,000 m^3 of shingle is transported along the beach in a 12-month period. This compares with the modelling which predicted the average longshore shingle transport to be 30,000–45,000 m^3 per year, with groynes. Notably, later modelling carried out for a separate (wider) coastal processes study using a different model to transform a longer offshore time series inshore determined average sediment transport rates to be between 20,000 and 25,000 m^3 per year. Both compare well with this actual transport rate, but indicate the magnitude of differences and thus accuracies attached to outputs that can result simply from application of different wave models and length of datasets.

The detailed scheme modelling does appear to have overestimated the amount of drift (and accumulation of material in the pocket), but this may also be due to the combination of a number of factors such as: natural variations in drift, how the model is able to replicate groyne efficiency, the initial recharge volume used, and the assumptions made regarding sediment input at the updrift boundary.

There were also fewer occurrences of large storm events after commencement of the scheme in 2004 than previously recorded, with the greatest difference being in the key wave direction driving material from west to east. From this it may be inferred that the modelling would have overestimated, rather than underestimated, the rates of sediment transport and therefore the recycling requirements. This may explain why slightly less recharge has been sufficient to maintain a reasonably healthy beach along the majority of the frontage, despite the initial recharge in the first year being much less than planned.

Calibration of the model was possible and it was found that the model was most successful using a smaller sediment size than the average D_{50} of the actual beach material. This was because information on actual beach behaviour with the proposed recharge material was available (this not coming from a remote source).

Change in schedule of works

A crucial reason for the difference in scheme performance from that expected is the fact that the schedule of works, and in particular volumes of recycling, altered from that originally planned. Although this was a risk recognised by the project appraisal report (PAR), it was not specifically considered in the modelling.

The original aim was for a large capital recharge and subsequent maintenance of the beach, but constraints meant that the beach build up programme had to be spread over eight years rather than one.

The eventual volume placed on the beach in year 1 was only a third of that intended and subsequent recycling was also been less than originally planned. This is at least partially due to the limited availability of shingle depositing within the extraction pocket.

Modelling, combined with engineering judgement, did indicate that construction of groynes were likely to cause downdrift impacts along this frontage. The schemes success was therefore very much dependent upon adequate recycling to ensure that groyne bays were filled and therefore sediment transport was not being totally inhibited. A review of the model runs also reveals that modelling showed that a large initial recharge was important to the success of the scheme.

The construction of groynes also varied from the original schedule, with commencement and completion delayed. The modelling had specifically identified the importance of groynes to prevent downdrift cut back. They were not constructed initially and erosion was experienced, resulting in the need for transitional groynes. Elsewhere, there were also problems of shingle loss and beach narrowing prior to groynes being constructed a year later than planned.

Calculations of beach material for the initial beach recycling were based on beach monitoring data up to 2000. The scheme did not, however, commence until 2004 and therefore the baseline conditions could have altered which may explain why only 30,000 m^3 was recycled in year 1 rather than the 90,000 m^3 proposed.

Sediment input at updrift end

Historical evidence suggested that at the updrift (west) end of the frontage the beaches tended to remain relatively stable, but since 2008 there have been issues with beach lowering here. When modelling the options, an artificial feed of sediment had to be fed into this boundary to replicate this stability. However, it was noted that this was a large uncertainty and that the model was also very sensitive to changes made to this boundary condition. It has been suggested that the impact here may be due to a reduction in sediment received from further west, as a result of another scheme constructed at a later date (so not included in the modelling) interrupting some shingle, or even some fines, being transported alongshore. Another possibility is that that new groynes within the Pett scheme are interrupting some occasional westward shingle transport of shingle that was not picked up in the modelling. It is also possible that this is not a long-term issue and there is anecdotal information that some shingle is starting to be moved around the headland here.

The PAR report recommended that management of the frontage should be adaptive to take account of uncertainty in the model, with regard to the variability in annual drift rates and the uncertainty regarding sediment feed at Cliff End.

Lessons

The timing of scheme construction relative to completion of modelling studies can have an impact on the predicted behaviour of the scheme – in this case because the initial recycling volume was so dependent on the available of material in the source area and potentially as baseline conditions may have altered in the interim period. Where a scheme does rely on such accurate information, it is important to ensure that the most up-to-date information is incorporated prior to construction, with the impacts of any change fully considered.

The extensive modelling of this coast led to a greater understanding of the processes and beach response. So although the scheme did not follow the proposed plan of works, the model runs provided a large amount of information to inform decisions on how to respond to the change in scheme. This information should subsequently continue to be used by coastal managers.

Modelling can indicate where the uncertainties lay and the potential impacts of these uncertainties on potential beach behaviour. Here, this appears to have led to a more flexible scheme being developed, with a heavy emphasis on monitoring. The final scheme design also allowed for additional groynes to be incorporated should monitoring support their requirement. This type of flexible approach is advocated where there are a number of uncertainties to be accommodated.

Calibration of the model was most successful in adopting a smaller sediment size in the model than the actual material on the beach. Although this would be an issue on beaches replenished with dredged sediment, it would be acceptable where native sediment is the source of nourishment material.

Although there is debate about the suitability of one-line beach plan shape models for use on shingle beach, the application here appears to have been successful. This is most probably due to the fact that the beach model could actually be calibrated successfully.

A.8 Prestatyn

What will I find in the case study?

This is an example of a scheme designed based largely on local knowledge and experience without the use of numerical models (other than offshore wave climate). The design was for a one-off capital recharge on a beach stabilised with rock groynes.

Overview of scheme

Design

The 1993 scheme consisted of raising rock groynes and importing beach recharge from licensed dredging areas for placing between the groynes to improve beach levels.

It is believed that desk study and empirical design approaches were used, with modelling (of waves) and data collection carried out to provide design parameters. No beach modelling is known to have been undertaken, with scheme design based on the empirical methods and engineering judgement.

Performance

Non-engineering decisions made at the time meant that approximately double the volume of beach material intended was actually placed during the nourishment. The original contract was for the importation of 110,000 m^3, but approximately 210,000 m^3 was placed. It appears this was a case of being opportunistic as it was affordable to do so due to the price of tenders rather than any evidence that more material was actually needed.

The combination of rock groynes and beach recharge has since acted to stabilise beach levels across the frontage, with the rock groynes playing a key role in the observed behaviour.

Since construction no beach management has been necessary. During that time there have been areas of beach where volume has risen or fallen but that behaviour is cyclical. Overall across the frontage beach volumes at present are greater than when the nourishment was completed.

Additional points of note

Beach material selection criteria were for material with a D_{50} greater than or equal to the existing beach material (sand). Offshore dredged sand was used though there are no records of actual grading.

Wave records indicate that wave height exceedences were greater in the years immediately preceding the scheme than those post-scheme, indicating that the beach has been subject to less wave energy than might have been expected. But without specific pre-scheme performance predictions, it is not possible to identify the impacts the difference in conditions has had on scheme performance.

Assessment

Key findings

Overall the behaviour of the beach has been as expected, although there are no predictions of behaviour against which comparisons can be made. Pre-scheme calculations identified that there was a potential net drift deficit of approximately 60,000 m^3 between material entering and leaving the frontage. The scheme has turned this potential deficit into an average net gain of approximately 3,000 m^3 per year.

There is a difference in performance with the updrift (western) half of the frontage gaining material (≈ 4,500 m^3 per year on average), while the downdrift (eastern) half of the frontage has lost material (≈ 1,500 m^3 per year on average). This is believed to have been due to the westerly groynes intercepting drift immediately post-scheme and preventing material from moving further easterly. Analysis of the most recent data (2002-2008) suggests that ongoing drift is gradually being reinstated with only a small net loss over this period taking place across the easterly half of the frontage.

Across the downdrift frontage immediately east of the scheme limits, examination of data provided three key observations.

- Immediately downdrift there are two further rock groynes, where the beach was not nourished. The general effect on behaviour in this section has been neutral with the groynes stabilising levels across this section.
- Downdrift of the final rock groyne, over a distance of approximately 1 km, beach volumes have reduced, suggesting that the scheme has caused starvation in this area.
- Beyond the 1 km limit, drift mechanisms appear to have re-established and accretion is taking place.

The key to scheme performance has been the control on beach behaviour exerted by the rock groyne control structures. The structures have not blocked all the drift but have acted to maintain improved beach levels across the frontage, while allowing natural process behaviour to be maintained.

Lessons

The scheme was carried out without any detailed modelling of scheme behaviour or performance, using a solid background and knowledge of local process behaviour allied with inputs from experienced key staff who had a good understanding of how the scheme was likely to behave. Without detailed modelling of the beach behaviour it is possible that the scheme design may have been more conservative.

The key lessons to be learnt from this scheme are as follows.

- In many aspects, specific local knowledge and experience can be equally important as detailed modelling, although a thorough understanding of process behaviour and likely scheme impacts backed up by empirical calculation and judgement are essential.
- Detailed and in some cases expensive modelling may not always be necessary.
- Consideration of all available design tools, including modelling, is important at the outset to ensure that the design is based on the best possible understanding.

A.9 Preston Beach (Weymouth)

What will I find in the case study?

This is an example of a scheme that was comprehensively modelled but has responded differently from expected in both alongshore and cross-shore directions, in part owing to its orientation relative to wave direction and differences in the wave climate, and the use of different sized and wider graded renourishment material. In this example an unusual but effective approach was taken to address the problem of cliffing of the beach resulting from the high fines content in the recharge material.

Overview of scheme

Design

The scheme comprised a capital beach recharge of 214,000 m^3 of dredged material spread over a 1.4 km length with a terminal rock groyne constructed at the southern end of the scheme to intercept southerly drifting material. Material accumulated here was expected to need to be redistributed across the beach every 7–10 years. A series of hydraulic model studies were carried out to test the proposed designs and to fine tune designs for maximum cost effectiveness and hydraulic performance.

Scheme design was based primarily on 3D and 2D mobile bed physical modelling, supported by interactive numerical modelling of sediment transport. Drift calculations were used to calibrate the physical model sediment transport rates. A range of beach geometries were considered, analysed by sensitivity testing of a range of storm events and storm profiles.

Initial modelling was based upon a single survey of the beach undertaken prior to modelling in 1994. No data were available to calibrate the sediment transport in the beach plan shape modelling.

Performance

The as-built scheme (1996) reflected all the geometric and volumetric details developed at the design stage; being based closely on the physical model. However, the beach recharge material had a D_{50} of 11 mm and a sand content of approximately 45%; the modelled sediment had been scaled to be representative of a material with D_{50} of 15 mm and without any sand content. There were rapid changes to the cross-shore profiles and formation of steep scarps at the upper beach along much of the frontage.

Following construction, it was soon found that a crest width of 25 m along 600 m of the north-eastern part of the frontage was unsustainable due to insufficient understanding of the general wave climate, drift reversals and location of drift divide along this section, thought likely to in part be a direct result of the lack of available data to calibrate the original model. Rapid reductions in the crest width occurred within 12 months, which reduced the crest width by up to 13 m at some locations, requiring high levels of maintenance to maintain the designed berm widths. Subsequent assessment suggested that a crest width of only 15 m can be sustained along this part of the frontage. The beach is generally stable now except under southerly waves, where material is transported to the north east in front of Furzy Cliffs. This material is then lost to the recharged beach unless brought back through intervention. Such intervention occurs on average 2–3 times per year.

Accumulation of material has occurred to the north east, with clear evidence that there has been significant net transport direction towards the north for the whole of the period following recharge, that is, in the opposite direction to that predicted. Limited realignment of the beach is also evident to the south-west of the site with signs of a build-up, adjacent to the terminal groyne, soon after construction. This zone has subsequently stabilised and has remained unchanged during the past 10 years.

The northern parts of the recharge area have undergone rapid erosion and evidence suggests that material is moving both to the south-west and the north-east, and suggests a drift divide at the site, over this period.

Additional points of note

Preston Beach forms part of a complex sediment transport system operating within the wider Weymouth Bay, the exact nature of which is subject to some debate and uncertainties remain unanswered.

Assessment

Key findings

Observations have demonstrated some significant differences between monitored performance and predictions at the design phase. Many of the differences in performance are interlinked.

The measured net drift direction is in the opposite direction to that suggested by the design stage beach plan shape modelling. This is demonstrated by gradual accretion to the north-east of the site and loss of material from the zone at the north-east end of the recharge and supported further by the requirement to regularly recycle material from the area to the north-east of the recharge site.

Longshore transport tests and beach mathematical models were tested using morphological averaged conditions based on wave climate statistics to determine rates of longshore transport and potential longshore losses. This suggested that beach transport will occur in both directions, with a small net transport typically to the southwest. The frequent drift reversals indicate that the beach alignment is close to an equilibrium shape relative to incident wave conditions. However, the wave climate data did not include swell wave conditions, which will include conditions primarily from the west and south-west. Such conditions might reasonably be expected to drive sediment towards the north-east, since they will have originated from the south-west.

The actual longshore transport rates (1996-2012) have on average been significantly greater than the initial predictions suggested by the modelling (estimated at around 2,900 m^3 per year net towards the south-west). However, the observed changes based on monitoring are about 5,000–9,000m^3 per year towards the north-east. This might be considered a reasonable result relative to realistic modelling expectations in a low drift situation and where drift reversals are predicted by the model. But these differences have presented significant management challenges requiring much greater and more frequent intervention to recycle sediment along the frontage than was expected to be the case at the design stage.

Sediment transport rates that are 2–4 times higher than expected and in the opposite direction to that predicted seem most likely to be a function of the complex nearshore wave climate and the angle of approach relative to beach orientation; as such very small differences in the incident wave angle has significant effects on transport direction and magnitude. Sensitivity tests conducted in numerical modelling suggested that a mean change of $\pm 2°$ in alignment might result in an annual difference in transport of about $\pm$4,000 m^3 at this site.

Beach slopes differ from those modelled primarily because the grading of beach material and the consequent permeability are quite different to that tested. The physical model was designed with material with no sand content, while the beach was constructed with a high sand content; this does appear to have had an adverse effect on scheme performance, particularly in the first five years following construction.

Anecdotal evidence suggests that beach sieving works undertaken in 2001 along a 360 m length of the north-eastern part of Preston Beach have improved the situation. By removing some of the finer fraction of the material placed as recharge, the beach is better able to absorb wave energy. Fewer reports of beach cliffing have been reported since this activity took place, although it is still quite common along the frontage. The impact that the finer material was having on permeability and beach response is acutely apparent from the fact that despite a quantity of 18,000 tonnes of beach material being removed, beach surveys indicate minimal change in the overall beach volume over this period.

The level of intervention required to maintain the beach crest has been greater than anticipated, but the establishment of a Beach Management Plan in 2009 gives the Environment Agency the certainty that the maintenance work it undertakes is targeted and adaptable to suit changes in Weymouth Bay into the future. The monitoring programme has provided timely and detailed assessment of performance and has enabled a more reliable assessment of rates of loss from the system and provides better opportunity for planning of maintenance and future model validation.

Lessons

Where possible, the available material should be ascertained prior to modelling so that the model reflects the final beach delivered.

Available data prior to modelling was clearly inadequate, but the timing of the design was out of the control of the modellers. Ideally modelling should be delayed if appropriate field data are not available. Incorrect assumptions have led to the need for remedial works and much higher levels of ongoing maintenance than assumed would be the case in the design.

Where drift is generally considered to be at a low rate for an open coast, attention must be given to gross transport rates too, especially where very small changes in wave approach angles might result in quite different conclusions regarding direction and thus management of that beach.

Although sediment transport rates calculations may lie within the expected range of outputs from the models applied, it would be beneficial if any susceptibility to variability were clearly highlighted in reporting the results. Model reporting is usually somewhat more matter of fact and does not reflect on the uncertainties or limitations with the approach. Some form of sensitivity assessment would be helpful to identify the range of potential outputs. The range of sensitivity values to be tested could be guided by identification of the expected available sediment source/grading prior to modelling.

Returning to a beach to subsequently remove finer material to address permeability and performance issues is rare, due to the costs of doing so. But this might be an option to be considered in future with these costs compared against the costs of the likely levels of management activity from not doing so. Unfortunately information on this exercise is largely anecdotal, and while valuable, such an unusual operation merits more rigorous monitoring of changes in performance. This very issue is at the crux of the relative performance of shingle and mixed sand and gravel beaches. Any further repetitions of such activities should be supported by a carefully designed monitoring programme. The observations do also appear to support the suggestion that different design tools are required to assess the performance of mixed sand and gravel beaches.

Design stage action triggers cannot always be achieved in accordance with the design.

The first target should be to achieve the action trigger level with the design slope and a crest width/level. If this is not possible then it is essential that management options are explored with the aim of restoring the beach to at least the action level. If this is not possible, the beach should be re-profiled to the best possible profile, with the aim of at least protecting the seawall and promenade, by providing more than the emergency trigger level.

A.10 Seaford

What will I find in the case study?

This is an example of using both physical and numerical models when some of those approaches were in their infancy (mid-1980s) to design a scheme at a location with a long history of beach erosion and depletion, potentially compounded by previous activities. The site itself is a largely enclosed bay, with man-made controls to both east and west, but subject to variable longshore drift within that bay, with the potential to reach a stable equilibrium state prevented by a seawall protecting developed areas.

This example shows the importance of identifying the right parameters and data for modelling and illustrates the appropriateness of identifying and stating known uncertainties in outputs at the time of design.

Overview of scheme

Design

The scheme involved a beach recharge of approximately 1.5 million m^3 of mixed sand and gravel over a frontage length of 2.5 km, together with a large concrete terminal groyne at the eastern boundary. The western boundary was already fixed by the arm of Newhaven Harbour to provide a self-contained system largely isolated from regional sediment supply. The eastern harbour arm is, however, partly permeable. The historic seawall alignment restricts cut back to a stable bay shape and insufficient space is available in front of the wall to enable the beach to form an equilibrium bay shape. The varied bathymetry along the length of the site and the influence of the breakwater at the western end results in differing wave climate and beach response from east to west, with wave energy directed towards both extremities.

Scheme design was based on an extensive programme of modelling which included:

- mathematical modelling of the offshore and nearshore wave climate
- physical modelling of alternative cross section and plan layouts
- numerical modelling of sediment transport and beach plan shape evolution

The whole site was too large to model as a single physical model section at a suitable scale, so this was restricted to a selected portion of the frontage modelled with a 1:60 scale 3D physical model. This only permitted a limited range of situations to be tested which could not be fully representative of long-term patterns. Therefore a numerical one-line beach plan shape model was used to assess the morphological evolution of the beach and perform drift calculations that could be used to calibrate physical model sediment transport rates. In addition to the initial recharge requirement, the modelling work identified a design cross-sectional profile for the beach which was subsequently used to inform maintenance requirements.

Based on the modelling results, the requirement for annual recycling was identified, with drift rates indicating this might average 28,000 m^3 per year potentially rising to 46,000 m^3 per year. A responsive recycling policy was planned, with quantities being governed by actual rates of drift and erosion. No further recharge was envisaged.

Performance

The as-built scheme reflected all the geometric and volume characteristics developed at the design stage, being based closely on the physical model. Losses of some 15% of volume (approximately 200,000 m^3) were anticipated within six months of scheme completion, mostly due to removal of fines, recognising that material generally available from offshore dredging sources would contain a significant proportion of fine material. The expectation was that the fill material would be sorted by wave action until the grading approximates to the indigenous material. A pragmatic assumption was made that the eventual volume of the recharge might be reduced by about 40% following winnowing of material beneath a size of 4 mm with time. But, despite some annual losses and gains, overall beach volume has remained roughly constant since 1987.

The planform that has developed shows regular accumulation of material to the east and west ends of the frontage. Erosion is predominant in the central section of the recharge site. This is as predicted by the modelling, but the rates have been much faster and the maintenance commitment to recycling is much greater than expected, of the order of 50–125,000 m^3 and on average three times that predicted.

Beach profile response to storms has been very close to that predicted by modelling of similar wave characteristics. However, there are rapid changes to cross-shore profiles and the formation of steep scarps at the upper beach where this becomes less permeable, primarily as a result of the recycling activity which causes compaction of the crest and binds recycled fine materials into a cohesive matrix. This cliffing can undermine the beaches ability to respond to storms as expected and necessary. This has recently been addressed by re-profiling works and breaking up some of the top layer of compacted material.

Additional points of note

The main difference between the modelling and the as-built construction was the grain-size distributions of the modelled and the prototype recharge material. The physical modelling was based upon sediment scaled to be representative of a shingle grading with a D_{50} of 14 mm, but without the sand content and an effective cut off of material below a grain size of about 6 mm.

The design or grading was not modified to reflect the anticipated high fines content. The following observations were offered at the time on the impacts of finer wider graded material to that tested.

- The beach may be expected to form a dynamic equilibrium slope at a shallower angle and lower crest than achieved by the modelling. This could require a larger quantity of material to form the capital recharge.
- The longshore sediment transport rate may be higher than expected by calculation in the modelling. Losses from the system could be greater, therefore. This would result in a requirement for more frequent and higher volumes of maintenance to be included in the beach management plan.
- The use of a finer grading or a more widely graded material would reduce the permeability of the beach and reduce the effectiveness of cross-shore performance.
- More widely graded materials would contain a higher proportion of fines, which are likely to be lost from the system at an early stage.

These assumptions were not, however, tested in either physical or numerical models.

Assessment

Key findings

Overall performance

The beach volumes have remained fairly constant over a period of 25 years and the design beach geometry conditions have been maintained.

The need for a responsive recycling strategy has also been shown to be correct. Maintenance commitments are, however, much greater than the modelling suggested. This difference can be attributed partially to the wave conditions used in design, which have not been representative of the more energetic post-scheme wave conditions. In addition, the high fines content within the recharge volume is likely to have resulted in faster transport rates than originally modelled. It should be noted that this was a design phase expectation.

This might be considered a reasonable result relative to realistic modelling expectations, in a high drift situation. The potential for such differences are also highlighted in the design reports, which explain the uncertainty associated with a variety of variables in a clear manner.

Wave climate

There is clear evidence that the time series used in the design phase has not been representative of the period following construction. The wave conditions since scheme implementation have been generally more energetic than those modelled at the design stage; there has been a greater frequency of severe storm conditions than expected; and, the design offshore (1:100 year) significant wave height, as calculated at the design stage, has been exceeded several times since scheme construction in 1987.

The general suggestion of longshore variability of wave energy, provided by the wave models, is supported by clear evidence of variability of longshore transport rates along the length of the beach recharge.

Plan shape evolution and sediment transport

Plan shape evolutionary trends have been similar to that suggested by the beach plan shape modelling process, although the central section has cut back much further than anticipated within the modelling.

The longshore variability of sediment transport rate has matched that anticipated at the design stage; this is evidenced by a build-up of material at both ends of the bay. However, the sediment transport rates have been generally higher than predicted by the beach plan numerical model. Consequently recycling rates have consistently been several times greater than originally envisaged at the design phase. In parallel with monitoring, further assessments were made of the plan shape modelling. This modelling based on data from 1988-1991 indicated that, to achieve the measured drift rates of about 70,000 m^3 per year, the model Kl factor for sediment size needed to be adjusted from 0.02 to 0.04.

Cross-shore performance

Cross-shore responses have been broadly similar to those modelled, but cut back of the beach crest has been greater than that modelled in moderate conditions. Beach slopes differ from those modelled, however, and the lower beach slopes are generally flatter than modelling of shingle with no sand fraction might suggest. Even under quite moderate wave conditions the upper beach has tended to form extremely steep cliffs where the fine material has been bound into a matrix with the coarser fraction of sediments.

The consequent permeability is quite different to that tested in the physical model due to the higher presence of finer material (40% sand content in the initial recharge). Limited and very slow infiltration of waves was observed into the beach early on. More recently it has been suggested that the lack of permeability has accentuated wave run-up.

Lessons

Although the time series of wind data and measured wave data was the best available at the time of scheme design, the dataset was somewhat shorter than is desirable for a project of this type and the time series was not representative of the more severe conditions that actually occurred during the subsequent 10 years. Ideally a duration of 20 or more years of data should be used, enabling inter-decadal variability to be considered. This is generally possible now for open coast sites using one of the long-term Met Office offshore datasets; these also include swell waves, which can be significant at some locations. This approach will improve the ability to model sediment transport more accurately, since this is strongly dependent on wave height and direction.

Where possible, measured wave data should be used in design to complement numerical hindcasts to assess systematic bias in modelled data and to validate those data once transformed inshore.

The bathymetry used for modelling transformations should be carefully scrutinised and validated against any measured data where possible; this will restrict the possibility of wave directions being incorrectly represented by the modelling.

Transport rates at this site are significantly higher than expected, requiring much higher rates of recycling than planned; the difference in the actual and modelled rates possible reflecting a combination of differences in wave climate, sediment size and perhaps model calibration for grain size. Some form of sensitivity assessment would be helpful to identify the range of uncertainty relating to these differences, which could then be accounted for in the decision making and implementation process.

Monitoring at this location illustrates the value of comprehensive field observations as an integral part of calibrating and updating the modelling, particularly at complex sites such as this.

A.11 Southend-on-Sea

What will I find in the case study?

This is a beach recharge scheme in an estuary with a coarse shingle beach sitting above sand at the back of a wide intertidal mudflat, resulting in different wave conditions and beach response than might be seen on the open coast. This is also an example of where the lack of data at the time of design to drive and calibrate models has resulted in some conservatism in the prediction of future maintenance which has not proved to be necessary to the extent expected.

Overview of scheme

Design

Modelling of options considered groynes or an open beach along the 2.2 km frontage. However, an open beach solution was preferred, in part due to the environmental benefits of avoiding the need for maintenance plant to track across the foreshore seaward of the groyne ends which forms part of an internationally designated site. There was also concern that the beach recharge material could spread and smother areas of the inter-tidal flats. The specification of the grading of the recharge material was therefore optimised to maintain a stable steep profile and avoid significant loss of fines onto the sand/mud flats.

As a coarse sediment beach was planned, it was expected that wave driven sediment transport on the beach would be the dominant process. Due to the relatively sheltered location in the outer Thames, both swell and locally generated waves needed to be considered. Modelling of wind wave hindcasting of estuary generated waves using local wind data and transformation of offshore wind and swell waves from the Met Office model were undertaken and used to derive a combined nearshore wave climate. There were though no measured inshore wave data available for use in the modelling or to help calibrate the models.

The beach profile was optimised through modelling tests and knowledge of the existing and nearby beaches. Design was undertaken using used two cross-shore profile models to represent the beach response to storms; a numerical model for sand sized sediment (2 mm) and a parametric model for gravel (2–10 mm).

A one-line beach plan shape model was set up, but as only one set of beach profile surveys was available, there was insufficient data to calibrate this and output was limited to comparing predicted drift directions and shoreline change to evidence of transport directions from observations during a site inspection. This showed that longshore drift rates were low due to the dissipation of wave energy and refraction of wave directions towards shore normal by the extensive mudflats. Predicted maximum drift rates were 2,000–3,000m^3 per year.

Expected rates of sediment transport and thus recycling/recharge top-up requirements were uncertain due to the lack of data to calibrate the numerical models. A contingency was therefore added to the modelled estimates and it was considered that recycling of beach material may be required on an annual basis, with an expected total of 40,000 m^3 of recycling over each five-year period. Additional recharge of 15,000 m^3 was also allowed for at 10-year intervals.

Performance

The estimated total volume of material required for recharge was 190,000 m^3, with a defined placement profile. This was undertaken in 2002 as designed, providing a beach crest level of 0.25 m above the design profile and the levels to trigger beach management action specified in the beach management plan.

The specification of the grading envelope was amended slightly to better take into account the available sediment from the offshore dredging site. However, the changes from the specified envelope were minor.

No recycling was required over the first four years. There was some natural re-profiling on the beach and some small movement of material eastwards; however, the action thresholds were not met. In year 5, a storm resulted in part of the crest falling below the action level, but the length affected was less than the threshold for action. Following some further beach erosion, 6,000 m^3 of beach material was recycled in year 6 from an area of accretion further east. A later survey indicated that the beach profile had not been restored to the design profile at the extraction or deposition locations. It appeared that material was extracted from the beach crest and placed on the active beach, resulting in additional lengths not meeting the trigger levels for the crest.

Since then overall beach volumes appear to remain healthy, but although further re-profiling has been recommended to meet crest level targets, little or minimal further beach management work has been undertaken (possibly due to funding constraints). By year 10 it was noted that the volume on the beach still appeared to be sufficient for re-profiling and recycling to restore the beach to meet the crest level targets.

Additional points of note

In year 5, a pier thought to be a retaining/control structure for the beach material was removed. The effects of the removal of this structure, which had sheltered part of the frontage and led to localised build-up of the beach, was considered. It was expected this would become distributed over subsequent years, although no modelling was undertaken. Although coincident, the removal of this was not related to the need to recycle. However, there had been a build-up of the beach to the west of the pier, which as expected dispersed towards the east after the pier was demolished. The dispersal of this material further east essentially meant that future recycling to the west end of the frontage would need to source the material from further east.

Assessment

Key findings

The extent of actual beach management works has been less than expected, in large part due to some conservative estimates of future beach management activity made as a result of a lack of calibration data and the short period of wind/wave data at the time of design.

There was an unusually low level of storms during the three years after construction, which also appears to have resulted in a difference between expected and actual performance. The three years following completion of the scheme had a comparatively benign wave climate compared with the rest of the wind/wave record. Consequently no beach management works were required until year 5 and the cumulative volume of beach management works still remains significantly less than expected.

When a significant peak in extreme waves did occur, erosion was seen at the west end of the frontage. While the beach management plan was not specific about where the recycling would be required from or to, the modelling had predicted a loss of material to the east, which is consistent with the findings.

Although a very short period of wave record was used for the design studies, the storm conditions during the five-year period used does appear to have been reasonably representative of the more severe conditions occurring in the overall 23-year data period (up to 2012) which has been subsequently examined. However, this was by chance rather than design; longer term data (up to 10 years) might have been used at the time but were not, possibly due to budget limitations. If the longer term wave data had also been used, it is likely that estimates of future recharge/recycling may have reduced slightly.

However, the beach has remained relatively stable, which is as predicted. The sheltered nature of the site and protection by the extensive sand and mud flats of the outer Thames estuary at low tide were expected to result in limited movement of the beach recharge material. This has proved to be the case.

Lessons

The wave and sediment transport models were not calibrated as there were no measured data in the vicinity. A conservative view was therefore taken on beach management activity. Although the scheme has required less beach management than allowed for and actual costs are less than expected, a conservative approach can lead to the overestimation of costs which could make a scheme appear less well economically justified than is actually the case.

Only five years of wind and wave data were used in the modelling study that informed the design. This is not generally considered to be long enough to reliably derive the mean or the range of the expected annual wave climate. Although by chance the period of data used was reasonably representative, if relatively energetic, this may have led to high estimates of sediment transport and added to the conservative nature of the design. It is recommended to always use a dataset as long as possible and a minimum of 10 years.

Beach behaviour in an estuary environment can potentially be affected by locally generated and open sea wave activity. These need to be effectively combined to fully represent the environmental characteristics at the site in any modelling; otherwise unexpected beach behaviour may occur and need to be managed.

Wide intertidal flats will have a significant effect on wave energy and direction. Consequently, gravel beaches sitting behind these may be less affected by regular conditions and only susceptible to cross-shore or alongshore movement from infrequent storm events. However, this same threshold to mobility will then also apply to the beach recovery, which means that the potential for natural recovery may be limited as the necessary energy to enable this does not occur at the site. Modelling should therefore consider this possibility too for informing the beach management planning.

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

Published by:

Environment Agency
Horizon House, Deanery Road
Bristol BS1 5AH
Tel: 0117 934 4000
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk

Would you like to find out more about us, or about your environment?

Then call us on
08708 506 506* (Mon-Fri 8-6)

email
enquiries@environment-agency.gov.uk

or visit our website
www.environment-agency.gov.uk

incident hotline 0800 80 70 60 (24hrs)
floodline 0845 988 1188

* Approximate call costs: 8p plus 6p per minute (standard landline).
Please note charges will vary across telephone providers

Environment first: This publication is printed on recycled paper.