Cyfoeth Naturiol Cymru
Natural Resources Wales

Advice to Inform Development of Guidance on Marine, Coastal and Estuarine Physical Processes Numerical Modelling Assessments

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Report No 208

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Contents

Crynodeb Gweithredol 6

Executive Summary 8

1. Report scope and purpose 10

2. Review of existing coastal numerical modelling guidance 11

3. Types of models 18

    3.1 Categories of models 18

    3.2 Dimensionality of models 21

    3.3 Examples of proprietary and open-source models 22

    3.4 Applicability and data input requirements for 1D, 2D and 3D hydrodynamic, sediment transport and water quality models 25

4. Best practice in numerical modelling of coastal areas in support of EIA studies 27

    4.1 Choice of numerical modelling approach and model set up 27

    4.2 Specification of model domain 30

    4.3 Choice of modelling mesh 32

    4.4 Model boundary conditions 35

    4.5 Model parameterization 36

    4.6 Model verification 37

    4.7 Model calibration 37

    4.8 Model validation and quality assessment 39

    4.9 Number and length of model runs 41

    4.10 Modelling scenarios 43

5. Establishing a physical processes baseline to support modelling 45

    5.1 Types of data required 45

    5.2 Bathymetric data requirements 49

    5.3 Hydrodynamic data requirements 52

    5.4 Sea bed characterization requirements 55

    5.5 Sediment transport data requirements 57

6. Error, uncertainty and confidence in model results 58

7. Combining numerical modelling results with other methods of assessment 59

8. Conclusions and recommendations 61

References 63

Appendices 77

List of Tables

Table 1. Principal documents relating to coastal, estuarine and shallow marine modelling guidance 12
Table 2. Examples of models used in the UK for environmental assessment 23
Table 3. Model features and characteristics 24
Table 4. General applicability of different types of hydrodynamic model 26
Table 5. Major model input requirements for hydrodynamic (tidal) models 26
Table 6. Major model input requirements for hydrodynamic (wave) models 26
Table 7. Additional input requirements for sediment transport modules 27
Table 8. Additional model input requirements for water quality models 27

List of Figures

Figure 1. Schematic diagram showing how the interactive use of models and data contribute to provide increasing levels of information with increasing timescale 21
Figure 2. Illustrative stages in any potential scheme / intervention environmental impact assessment 28
Figure 3. Predicted far field effects on maximum water level arising from a tidal barrage in the Severn estuary 31
Figure 4. Examples of different types of gridding 32
Figure 5. Bathymetry of the Alde-Ore estuary used for Telemac2D modelling 34
Figure 6. Example of a composite LiDAR and bathymetric DEM of the Alde-Ore Estuary 51
Figure 7. Example of an up-to date bathymetric-topographic DEM of the Filey Bay area 52
Figure 8. Locations where tide, wind and wave data are presently being obtained in the UK ad adjacent waters 54
Figure 9. Summary diagram showing the complementarity of data-based approaches and modelling approaches in integrated environmental assessment 60

List of Appendices

Appendix A: Descriptions and capability summaries for selected models 77
Appendix B: Examples of typical modelling requirements for different scale schemes/ interventions 103
Appendix C: Summary of model modules, major input parameters and coefficients Required for the DHI modelling suite 119
Appendix D: List of acronyms and abbreviations 136

Crynodeb Gweithredol

Diben yr adroddiad hwn yw hysbysu datblygiad canllaw arfer gorau CNC i sefydliadau a allai fod yn ystyried defnyddio modelu rhifol i gefnogi Asesiad Effaith Amgylcheddol, Asesiad Rheoliadau Cynefinoedd neu asesiad y Gyfarwyddeb Fframwaith Dŵr yn ymwneud â datblygiad o fewn parth arfordirol neu ardal forol gyffiniol. Mae CNC wedi nodi'r angen am fframwaith arweiniad mwy manwl sy'n cynnwys yr agweddau canlynol:

- sefydlu llinell sylfaen prosesau corfforol i gefnogi asesiadau modelu
- dewis senarios model ar gyfer asesiad
- gweithdrefnau cynllunio, sefydlu a chalibradu modelau
- gweithdrefnau dilysu modelau
- sut ddylid dehongli canlyniadau modelu rhifol a'u defnyddio ar y cyd â gwybodaeth gan ddulliau eraill yn rhan o broses *Asesiad Integredig* cyffredinol

Mae'r adroddiad yn seiliedig ar adolygiad o ganllaw modelu blaenorol, adolygiad o'r mathau o fodelau rhifol sydd ar gael ar hyn o bryd a'r mwyaf cyffredin a ddefnyddir yn y Deyrnas Unedig i ymchwilio i hydrodynameg, cludiant gwaddod ac ansawdd dŵr, ac adolygiad o lenyddiaeth berthnasol a gyhoeddwyd. Yn seiliedig ar yr adolygiadau hyn, mae'r adroddiad yn gwneud nifer o argymhellion parthed y gofynion ar gyfer asesiadau a gefnogir gan fodelu o effeithiau posibl datblygiad mewn amgylcheddau arfordirol a morol.

Ni ddylid ystyried modelu rhifol o reidrwydd i fod yn ofyniad allweddol mewn asesiadau effaith posibl, yn arbennig yn achos cynlluniau llai ble na ellir cyfiawnhau'r gofyniad amser a chost o reidrwydd. Ni ddylai asesiadau fyth fod yn seiliedig ar fodelu rhifol yn unig, a dylid cymharu canlyniadau unrhyw fodelu rhifol gyda chanlyniadau o ddadansoddiad data a mathau eraill o ymchwiliad megis modelu ffisegol. Mae ansawdd a pherthnasedd canlyniadau modelu ariannol yn ddibynnol iawn ar safon y data a ddefnyddir i adeiladu a dilysu'r model, a dylai pob gwaith modelu gynnwys rhaglen o gasglu ac./neu goladu data. Dylid pennu'r gofynion posibl ar gyfer modelu rhifol, ac ar gyfer unrhyw gasgliad data newydd perthynol, yn ystod cam asesiad cwmpasau cychwynnol prosiect. Materion allweddol sydd angen sylw yn ystod y cam cynnar hwn yw graddfeydd gofodol ac amserol ar gyfer unrhyw fodelu gofynnol, y math gorau o fodel(au) i ddefnyddio er mwyn nodi llwybrau effaith posibl rhwng ffynonellau a derbynyddion, y senarios sydd angen eu modelu, a'r gofynion ar gyfer casglu data er mwyn caniatáu datblygu a dilysu model, ac i ddarparu ar gyfer defnyddio tystiolaeth annibynnol yn y broses gyffredinol o asesiad integredig.

Argymhellir y dylai CNC gynghori y byddai'n disgwyl gweld yr wybodaeth ganlynol wedi ei darparu mewn unrhyw adroddiadau a chyflwyniadau eraill a wnaethpwyd yn rhan o'r broses gynllunio ac/neu drwyddedu:

- diffiniad o'r broses dan sylw, amcanion yr astudiaeth
- diffiniad o fframwaith ffynhonnell – llwybr – derbynnydd perthnasol ar gyfer ymchwiliad
- adolygiad o'r sylfaen o dystiolaeth sydd ar gael

- cyfiawnhad dros y penderfyniad o a ddylid defnyddio modelu neu beidio
- cyfiawnhad dros ddewis y model a ddefnyddiwyd (ID, 2D, 3D ac ati)
- disgrifiad technegol o'r model(au), yn cynnwys hanes datblygu, enghreifftiau o ddefnyddiau blaenorol a phrofiad defnyddwyr y model
- y sail ar gyfer diffinio parth y model
- y sail ar gyfer y math o gyfuniad a ddefnyddiwyd
- y sail ar gyfer dewis amodau terfyn model
- natur unrhyw ddata presennol a ddefnyddiwyd (bathymetreg, lefelau dŵr, ceryntau, tonnau, nodweddion gwely'r môr, crynodiad gwaddodion a maint gronynnau, halltedd y dŵr, tymheredd a chrynodiad o unrhyw nodweddion perthnasol eraill (ffytoplancton, colifform ac ati), yn cynnwys eu cyfredededd, cydraniad gofodol a thymhorol, a gweithdrefnau a ddefnyddir i wirio ansawdd data
- natur unrhyw ddata newydd a gasglwyd, yn cynnwys dulliau mesur a gweithdrefnau ar gyfer rheoli ansawdd data
- natur a sensitifrwydd unrhyw brofion a gyflawnir
- sail ar gyfer dethol gwerthoedd paramedr model allweddol (e.e. garwedd y gwely, maint gwaddod gwely), a dull o gynrychioli yn y model
- dulliau a ddefnyddir ar gyfer calibradu'r model
- dulliau a ddefnyddir ar gyfer dilysu'r model ac asesi 'perfformiad' y model
- maint y gwallau / tuedd posibl yng nghanlyniadau'r modelu a goblygiadau posibl ar y casgliadau a wnaethpwyd
- cyfeiriad llawn at ddulliau archifo data a metadata, yn cynnwys disgrifiadau llawn o'r gweithdrefnau modelu y gellir eu harchwilio gan y rheolydd neu gyrff eraill os oes angen.

Executive Summary

The purpose of this report is to inform the development of NRW best practice guidance to organisations who may be considering the use of numerical modelling to support an Environmental Impact Assessment, Habitats Regulations Assessment or Water Framework Directive assessment related to a development within the coastal zone or adjoining marine area. NRW has identified the need for a more detailed guidance framework which includes the following aspects:

- establishment of a physical processes baseline to support modelling assessments
- choice of model scenarios for assessment
- model design, set-up and calibration procedures
- model validation procedures
- how the results of numerical modelling should be interpreted and used in conjunction with information from other methods as part of an overall *Integrated Assessment* process

The report is based on a review of previous modelling guidance, a review of the types of numerical models currently available and most commonly used in the UK to investigate hydrodynamics, sediment transport and water quality, and a review of relevant published literature. Based on these reviews, the report makes a number of recommendations relating to the requirements for modelling-supported assessments of potential development impacts in the coastal /and marine environments.

Numerical modelling should not necessarily be viewed as an essential requirement in potential impact assessments, especially in the case of smaller schemes where the time and cost requirement may not be justified. Assessments should never be based on numerical modelling alone, and any numerical model results should be compared with results from data analysis and other forms of investigation such as physical modelling. The quality and relevance of numerical modelling results is heavily dependent on the quality of the data used to construct and validate the model, and all modelling should be accompanied by a programme of data collection and/ or collation. The possible requirements for numerical modelling, and for any related new data collection, should be determined in the initial scoping assessment stage of a project. Key issues to be addressed at this early stage are the required spatial and temporal scales of any modelling which may be required, the best type of model(s) to use in order to identify potential impact pathways between sources and receptors, the scenarios which need to be modelled, and the requirements for data collection both to allow model development and validation, and to provide independent evidence to be used in the overall process of integrated assessment.

It is recommended that NRW should advise that it would expect to see the following information provided in any reports and other submissions made as part of the planning and/ or licencing process:

- definition of the problem being addressed, the study objectives
- definition of a relevant source – pathway- receptor framework for investigation

- a review of the available evidence base
- justification for the decision whether or not to use modelling
- justification for the choice of any model used (ID, 2D, 3D etc.)
- technical description of the model(s), including development history, examples of previous applications and experience of the model users
- the basis for the definition of the model domain
- the basis for the type of mesh chosen
- the basis for selection of model boundary conditions
- the nature of any existing data used (bathymetry, water levels, currents, waves, sea bed characterization, sediment concentrations and particle size, water salinity, temperature and concentration of any other relevant features (phytoplankton, coliforms etc.), including their currency, spatial and temporal resolution, and procedures used to check data quality
- the nature of any new data collected, including measurement methods and procedures for data quality control
- the nature of any sensitivity tests undertake
- the basis for selection of critical model parameter values (e.g. bed roughness, bed sediment size), and method of representation in the model
- the methods used for model calibration
- the methods used for model validation and assessment of ‘performance’ of the model
- the magnitude of possible errors / bias in the modelling results and the potential implications for the conclusions reached
- full reference to data and metadata archiving methods, including full descriptions of the modelling procedures which can be audited by the regulator or other bodies if required.

1. Report scope and purpose

Numerical models are routinely used within environmental assessment, including Environmental Impact Assessments (EIAs), Habitat Regulations Assessments (HRAs), and Water Framework Directive Assessments (WFDAs), to help understand potential changes to the hydrodynamic and sediment transport regime arising from a proposed development over a range of timescales.

Models vary greatly in type and complexity and it is essential that the model chosen is (a) appropriate to the environment and situation to which it is being applied, and (b) capable of reproducing the range of processes identified as important to the study, both in terms of the baseline environment and the potential impacts of a scheme.

The aims of this project, as stated in the project brief issued by Natural Resources Wales (NRW), were:

(a) to review existing guidance on modelling approaches including requirements for establishing an adequate baseline understanding to support modelling assessments, including model set up, calibration, validation and model run scenarios;

(b) to review and summarise key information on model type, applicability, set up, and limitations, for available models which can be applied to the assessment of effects on the hydrodynamic and sediment transport regime in marine, coastal and estuarine environments.

In order to achieve these aims, a number of tasks were identified:

- to compile a list of published modelling guidance currently being used in the UK for marine, estuarine and coastal environments
- a review of the relevant published modelling guidance to help determine best practice guidance on how to develop a modelling approach in consideration of factors such as project type and location
- a review of the types of numerical models currently available and most commonly used to determine the short term, medium term, long term, near-field and far-field potential impacts of a scheme intervention on each of:
  (i) Hydrodynamics (tides, waves, currents, wave/current interaction)
  (ii) Sediment Transport (cohesive and non-cohesive sediments)
  (iii) Water Quality (salinity, temperature, suspended sediment concentrations, contaminants)

The purpose of the review and advice provided in this report is to inform the development of NRW best practice guidance relating to:

- Establishment of a physical processes baseline to support modelling assessments
- Choice of model scenarios for assessment

- Model calibration procedures
- Model validation procedures
- How the results of numerical modelling should be interpreted and used in conjunction with information from other methods as part of an overall *Integrated Assessment* process

2. Review of existing coastal numerical modelling guidance

A number of reports have been published over the past 25 years with the aim of providing guidance on marine, coastal and estuarine modelling in the UK, although no Code of Practice or Standard has been developed and there is no formal national list of approved models of the type developed by the Federal Emergency Management Authority (FEMA) in the United States (e.g. see https://www.fema.gov/coastal-numerical-models-meeting-minimum-requirement-national-flood-insurance-program).

The principal documents of relevance to the development of coastal and estuarine modelling guidance in the UK, and which have been reviewed as part of this project, are listed in Table 1. It should be noted that this list does not include guidance documents relating to river water quality and flood modelling, which have been prepared on behalf of the Environment Agency (EA) and other organizations (e.g. Crowder et al., 1997, 2005; WAPUG, 1998;; Zaidman et al., 2005; EA, 2005; Neelz & Pender, 2010, 2013; . However, some of the principles outlined in these reports are relevant to coastal, estuarine and shallow marine environments. Where appropriate, account has also been taken of academic literature relevant to the issue (e.g. Falconer et. al, 1989; De Vriend et al., 1993; Reeve et al., 2004; Bates et al., 2005; Refsgaard et al., 2007; Dyke, 2007; Hunter et al., 2008; Chau, 2010; Amoudry & Souza, 2011; Roelvink & Reiners, 2011; Thomas & Dwarakish, 2015).

Some of the first attempts in the UK to model hydrodynamics and water quality were made in relation to the River Thames and its estuary in the 1950s, focusing on the dispersion and decay of faecal and total coliforms (Barrett, 1998). The approach was subsequently extended to other rivers, estuaries and coastal areas around the country. Initially the models used were two-dimensional and run principally by the Water Research Centre (WRc) at Medmenham. Subsequently a 2D finite difference water quality model (DIVAST), developed by Roger Falconer at Bradford University, based on an earlier model developed by the Rand Corporation, was made freely available and used by a range of environmental consultants, notably Bullen & Partners.

Table 1. Principal documents relating to coastal, estuarine and shallow marine modelling Guidance previously or currently used in the UK, and reviewed as part of this study

Authors	Organization	Sponsor	Intended application	Considered Timescales	Comments
Evans (1993a,b)	Water Research Centre	Foundation for Water Research	Shallow marine, coasts and estuaries- water quality	Short	Review and prescribed framework
Smallman et al. (1994)	HR Wallingford	Department of Environment	Coasts and estuaries - review of models	Short	Review of models
Cooper and Dearnaley (1996)	HR Wallingford	Department of Environment	Coasts and Estuaries - tides and currents	Short	Guidance
Lawson & Gunn (1996)	HR Wallingford	Department of Environment	Coasts and Estuaries - waves	Short	Guidance
Bartlett (1998)	Black & Veatch	Environment Agency	Estuaries	Short	Review and Guidance
Van Waveren et al. (STOWA) (1999)	Dutch Dept. of Public Works	Dutch Good Practice Modelling Study Group	General Water Management	Short	Review, Guidance, Job Recording Forms
EMPHASYS Consortium (2000)	Various	MAFF	Estuaries	Short, Medium, Long	Review and model summaries
Anon (2008)	ABPmer	DEFRA/ EA	Estuaries	Short, Medium, Long	Model summaries www.estuaryguide.net
Lambkin et al. (2009)	ABPmer and HR Wallingford	COWRIE	Offshore wind farms	Short	Best Practice Guidance
Anon (2013)	SEPA	SEPA	Coasts and Estuaries - discharges	Short	Guidance
Johnson (2015, 2016) Lawless et al. (2016)	Ch2M JBA	Environment Agency Environment Agency	Coasts and Estuaries Coastal areas	Short Short	Establishment of Standards for coastal and estuarine flood modelling Good practice framework for coastal flood forecasting

During the later 1960s and 1970s, scientists at HR Wallingford (HRW) explored the development of a range of computational models for application to river flooding, tidal processes, sediment transport and water quality (Abbott, 1979). During this period a number of European research institutes, including Delft Hydraulics and the Danish Hydraulics Institute (DHI, originally founded in 1964 as The Danish Institute for Water Production at the Technical University of Denmark), also developed models which also found application in the UK (Abbott, 1989). Over the same period, major efforts were being made to develop numerical and analytical models in the United States, Australia and elsewhere.

In the early 1990s WRc, acting on behalf of the Foundation for Water Research (FWR), undertook a review and prescribed a framework for estuarine modelling in the

UK, with a focus on water quality. Based on this review, guidelines were developed to assist members of the FWR in specifying marine and estuarine water quality models (Evans (1993a, b). The framework identified a series of key steps relevant to any modelling study:

- identifying the problem to be solved
- deciding whether or not to use a model
- definition of the scope of the model, including questions to be addressed
- specification of model dimensionality
- spatial and temporal resolution
- gridding and meshing methods
- specification of the Numerical techniques to be used
- data needs and acquisition, including definition of boundary and initial conditions
- model calibration and validation
- output and presentation of model results

Between 1993 and 1995 HRW was commissioned by the Department of the Environment (DOE) to review the computational models then available for engineering hydraulic studies in the UK, including current flows, waves and sediment transport, and to develop guidelines for best practice application (Smallman, 1994; Lawson & Gunn, 1996; Cooper & Dearnaley, 1996). This work included assessment of what type and complexity of model is best suited to particular real world situations and problems. The advice on application of models to tidal flow problems and sediment transport (Cooper & Dearnaley, 1996) included selection of area to cover, model resolution required, selection of boundary conditions, and selection of sediment transport model. In the case of sediment transport studies, Cooper & Dearnaley (1996) noted that there are three phases of investigation: (i) assessment, (ii) modelling, and (iii) field investigation. They noted that the assessment phase should always be undertaken first to determine the requirement for the other two; modelling and field investigations may or may not be required, may be required concurrently or one after the other. Assessment normally takes the form of a desk study–based literature / data review, sometimes accompanied by a field walk-over survey.

Later in the 1990s Black & Veatch were commissioned by the EA to undertake a similar review of computational models, which they took to include statistical and empirical models as well as numerical models. The report (Bartlett, 1998) noted that choice of model often has to be pragmatic, depending on a number of factors including technical suitability of software for a particular project, organizational policy on standardised software, availability of software in-house, cost and project budget, and staff experience / training. Several key stages were identified in the modelling process:

- project definition
- field data collection
- model construction
- calibration
- validation
- model application
- run referencing and archiving

In 1999 the Dutch Good Practice Modelling Study Group commissioned a report, published as STOWA Report 99-05 and Dutch Department of Public Works, Institute for Inland Water Management and Waste Water Treatment, Report 99.036, aimed at the technical modelling community concerned with general water management issues in The Netherlands (van Waveren et al., 1999). The report, which has been re-used by consultants in the UK, provides a step by step plan and checklist for the undertaking of water management modelling projects. The steps include:

- starting a model journal (project record)
- defining the objectives of the modelling project
- setting up the model
- analysing the model (including uncertainty analysis and validation)
- using the model
- interpreting the results
- reporting and archiving of the results and supporting documentation.

Phase 1 of the Estuaries Research Programme (ERP), co-funded by DEFRA, the EA and Natural England (NE), produced a *Guide to Prediction of Morphological Change within Estuarine Systems* (EMPHASYS Consortium, 2000a). This included a review and guidance relating to the tools available to assess short, medium and long-term morphological change in estuaries, including ‘Bottom-up’ process based methods, ‘Top-down’ conceptual and empirical methods, and ‘Hybrid’ methods. Chapter 2 of this Guide considered the major issues of interest to estuarine stakeholders, while

Chapter 3 discussed the information needed to address these issues. The issue of results interpretation, including confidence in model outputs and their uses, was considered in Chapter 5 and a worked example provided in Chapter 7. More specific information about individual modelling tools and approaches, including potential applicability, set-up requirements, necessary software and limitations, was provided in two parallel reports (EMPHASYS Consortium 2000b; Posford-Haskoning, 2001). Selected modelling approaches were subsequently examined in more detail during Phase 2 of the ERP (e.g. HR Wallingford et al., 2002), and a summary of the results provided via an on-line website (http://www.estuary-guide.net/).

Between 2002 and 2003 HRW, Posford Haskoning and Atkins undertook work as part of the DEFRA/ EA Research Programme for Flood Management aimed at providing best practice guidelines for coastal flood forecasting systems. The principal findings and recommendations were summarised in a Technical Report (HR Wallingford, 2004). Models were categorised in terms of the environment to which they are potentially applicable (e.g. offshore, nearshore, shoreline, land inundation) and in terms of their complexity (Judgement, 1st Generation, 2nd Generation and 3rd Generation, in order of increasing complexity). Data requirements for each type of model were identified, and recommendations made regarding the type and complexity of model required in relation to varying levels of flood risk. A list of ‘preferred’ models for each category of application was provided.

Building on general advice relating to requirements for offshore windfarm EIA studies issued by Cefas (2004), Lambkin et al. (2009) produced a best practice guide for coastal process modelling for specific application to offshore wind farm development, commissioned by COWRIE Ltd. The report provided guidance on the requirements for numerical modelling, and how to assess the extent and quality of any numerical modelling proposed and/or undertaken. Key issues identified in this context, to which modelling might be applied, were:

- suspended sediment dispersion and deposition patterns resulting from foundation and capable installation or decommissioning
- changes in coastal morphology due to cable landfall and maintenance
- scour and scour protection
- wave energy dissipation or focusing for sites close to the shoreline
- wave and current processes which may control shallow sandbank morphology.

The report emphasised that a critical initial assessment is to determine whether or not numerical modelling is needed and/ or feasible. With regard to feasibility, related questions are whether numerical models can represent the processes involved sufficiently well to provide the required information, and whether sufficient field data can be obtained to adequately calibrate and validate the model to provide confidence in the results. The need to achieve agreement with the regulator regarding the proposed modelling approach was also emphasised. Although aimed primarily at wind farm developments, much of the advice contained in this report is also relevant to other types of marine and coastal development.

The Scottish Environment Protection Agency (SEPA) issued Guidance in April 2013 relating to the modelling of discharges in coastal and transitional environments (SEPA, 2013). This Guidance emphasised the importance of defining the major issues and variables under consideration at the outset to select an appropriate model, and to define the requirements for data collection, model run duration, model domain (spatial extent), model dimensionality (1D, 2D, 3D etc.), and the required model grid (mesh type, resolution, nature of model boundaries and any structures present). The Guidance focused on hydrodynamic, water quality and particle tracking aspects, and no specific reference was made to waves, sediment transport, or morphological changes. A list of eleven critical steps were identified which any modelling study undertaken by SEPA should cover and receive explicit reference in reports to SEPA:

- statement of objective
- justification of the model used
- technical description of the model, including development history, examples of previous applications and experience of the model users
- the data required for the modelling
- the data collected, including measurement techniques, expected errors and quality assurance
- calibration procedures used, including the model coefficients calibrated
- validation procedures, including the nature for the validation datasets used
- sensitivity analyses undertaken
- quality assurance procedures used
- auditability – a full account of the modelling exercise procures to be available for inspection by SEPA
- reporting, including a clear description of the underlying principles and implicit or explicit assumptions of the model, a summary of the numerical output, the likely errors, bias, sensitivity and their implications for the conclusions reached.

Halcrow (2014), on behalf of the EA, undertook a review, of available beach behaviour models and their degree of 'success' in forecasting changes associated with beach engineering schemes, including groynes, breakwaters and beach nourishment (Burgess et al., 2014). The report concluded that the physics of beach models are generally sound, but that problems of poor prediction have sometimes arisen due to limitations of the data used with them, the application of the models, and the interpretation of results.

The EA also commissioned Halcrow (now CH2M) to develop standards for the modelling of flooding on open coasts and in large estuaries (Johnson, 2015, 2016), extending earlier work to develop similar common standards for flood modelling in rivers and inland areas. This work was undertaken in recognition of the fact that existing flood models are not designed to nationally consistent standards, with a lack of clarity of 'what is good enough', wide variability in model quality, and no systematic approach to model maintenance. Three types of model standard were identified:

- target quality standard, based on the intended use, which defines 'what is good enough'
- model quality standard, which measures how well the key flooding processes (Sources, Pathways and flood spreading to Receptors) are represented in the model
- model condition standard, which measures how up to date a model is in terms of key data, technology, flood events and capital schemes

Based on the model quality and condition measures, an overall model score can be assigned. Most of the models under consideration in these studies are area specific (e.g. Thames estuary flooding model interfaced to a Thames catchment model).

In parallel with this work, the EA commissioned JBA Consulting, HR Wallingford, the Met Office and the National Oceanography Centre (NOC) to produce a new Good Practice Framework to inform the development of future Coastal Flood Forecasting (CFFS) within the EA (Lawless et al., 2016). This included a scoring system for individual model sub-components and the overall modelling system, supported by a Decision Support Tool (DST). To date, no similar approach has been trialled for sediment transport and morphological modelling.

In recent years, several 'open source' computation models have been developed by the international model development community, principally consisting of researchers in universities and government funded research organizations. Several of these models are now widely used in the UK as part of research-driven investigations, and to a lesser extent in environmental consultancy. Applications of the models are to some extent regulated through the peer review process, but at present there is no formal guidance relating to their use.

Owing to the fact that, until very recently there were no UK "industry standards" for coastal, estuarine and shallow marine numerical modelling, and the standards currently being developed relate exclusively to coastal and estuarine flooding, many consultancy and research organizations have developed their own protocols for model set-up, verification, calibration, validation and quality assurance, taking into account the published guidance where considered appropriate. For example, in studies undertaken for the Swansea Tidal Lagoon EIA, ABPmer (2013a) used their own internally developed guidance for numerical model calibration (ABPmer 2013b) which incorporated elements of the earlier Foundation for Water Research guidance (Evans 1993a, b). In the absence of official Guidance relating to the modelling of hydrodynamic flows, waves, sediment transport and morphological change, this is an appropriate approach. However, some organizations may adopt a more rigorous approach than others, and differences in quality of results may arise due to different procedures used to develop and validate models.

3. Types of models

3.1 Categories of models

In general terms, a model is a simplified representation of real system which may be developed for demonstration, descriptive, hindcasting, real-time monitoring, forecasting or design purposes.

Several categories of models exist, including:

- physical models
- statistical models
- parametric or equilibrium models
- analytical models
- process based or ‘deterministic’ numerical models
- behaviour-based numerical models.

There is overlap between several of these model types, and in many studies more than one type of modelling is employed, an approach known as *composite modelling* or *hybrid modelling*, depending on whether individual modelling methods are used separately or in a functionally coupled manner.

The term ‘morphological model’ has also sometimes been used, in several different contexts. Some workers have used the term to refer to short term process-based models which are capable of predicting short-term changes in bed morphology (specifically bed level), sometimes with feedback updates to the flow and sediment transport modules of the model. De Vriend et al. (1993) used the term ‘medium-term morphodynamic’ (MTM) model to describe models which can predict morphological changes on timescales up to that of an individual tidal cycle or storm. In rare circumstances deterministic models have been run for up to a few months in real time, but this is computationally very intensive, and it cannot usually make realistic representations of time-dependent variations in the controlling processes, such as river floods or storm surges, whose frequency and magnitude is largely unpredictable on timescales of weeks or months. Some investigators have sought to predict longer-term changes in bed morphology (over years or decades) by extrapolating the results of short term modelling to periods of years or decades using a multiplying factor (otherwise known as a 'morphological factor'). However, such factors represent fairly crude approximations. None of the deterministic models currently available is capable of accurately predicting the complex three-dimensional changes in bedforms, including the position and size of banks and channels, which occur in natural systems, even on timescales of days. De Vriend et al (1993) used the term 'long term morphological model' (LTM) to describe behavioural numerical models which integrate processes at a higher level of aggregation and attempt to predict morphological changes over longer time scales (see below). However, such 'averaging' models are also subject to considerable uncertainty and potential error, often being impossible to validate.

Physical models are reduced scale representations of a feature and/ or process assemblage (e.g. a harbour which is subject to variable wave penetration, or an array of wind farm monopiles which may affect sea bed sediment movement). Discussion of physical models, their design and use for different applications is provided by Dalrymple (1985), Hughes (1993), Sutherland & Soulsby (2010) and Briggs (2013). An important requirement in physical modelling is geometric similarity, whereby all lengths in the reduced scale model have the same ratio as those in the full-scale system being modelled, and other characteristics are scaled using appropriate criteria.

Statistical models are widely used to predict the magnitude and/ or frequency of future events, including extreme sea levels, extreme waves, river floods or joint probabilities of these. A range of different statistical models have been used for this purposes (Coles, 2001) but all involve extrapolation into the future based on historical observations. Potential future changes in beach morphology have also been modelled using this type of approach (e.g. Masselink & Pattiarchi, 2001), and statistical analysis of storm data has been combined with outputs form a process-based morphological model (X-Beach) to predict medium to longer term changes in beach cross-shore profiles (Pender & Karunarathna, 2013). Such statistical or combined statistical -process based models can be run multiple times in order to assess levels uncertainty in the predicted outcomes (referred to as a probabilistic or Monte Carlo simulation approach (e.g. Dong & Chen, 1999; Lee et al., 2002).

Parametric models, sometimes referred to as equilibrium models, are relatively simple quantitative relationships between variables which may be used to predict change. Examples include the equilibrium beach profile concept (Bruun, 1954; Dean, 1991) and the Bruun Rule of shoreline erosion (Bruun, 1962). Many ocean-facing beach profiles approximate a concave form which can be described by the simple equation $h = Ax^{2/3}$, where h is the profile depth at a distance x from the shoreline and A is a constant related to grain size ($A=0.21D^{0.48,}$ where D is the median size in mm). Similar relationships have been identified between the beach form and wave conditions (Dean, 1991). The simple Bruun Rule relates predicted shoreline recession (Δx) to sea level rise (ΔS) by the expression $\Delta x = (L/d_c)\Delta S$, where L is the initial equilibrium profile length to the depth of closure, d_c. Another example is provided by the O'Brien (1931) formula which links estuary tidal prism (P) to the cross-sectional area of the mouth (A_E) by the relationship $A_E = CP^n$, where C and n are empirical coefficients.

Analytical models involve exact solutions to governing differential equations, and are often more time consuming and computationally expenses to run than numerical models (which use approximate solutions) if numerous processes and or environmental variables are considered. For this reason analytical models have often been restricted to relatively simple or small scale problems, such as long-wave run-up on a plane beach (Carrier et al., 2003), plan form development of crenulate beaches (Wind, 1994), or dune erosion due to wave impact (Larson et al., 2004).

Numerical models can be divided into two main sub-categories: (1) *process-based (or deterministic) numerical models*, and (2) *behavioural numerical models*. Process-based numerical models represent the significant processes relevant to the problem under investigation, typically over relatively short timescales (seconds to a few weeks or months), and for reasons of computational efficiency employ approximate solutions to the key equations relating the variables within the modelled system. The process-based numerical models used in shallow marine, coastal and estuarine environments can be broadly separated into:

- hydrodynamic tidal (or tide plus fluvial) flow models
- hydrodynamic wave models
- sediment transport models
- morphological models, which also include changes in bed levels due to sediment transport, sometimes incorporating feedback links to the hydrodynamics and sediment transport
- water quality models
- ecological models which incorporate biological processes.

There is considerable overlap between the different model types and the more complex modelling suites consist of modules which can be coupled to investigate combined processes and resulting changes in the attributes of interest. In general, there is much greater complexity and greater uncertainty involved in sediment transport, water quality and ecological models than in simple hydrodynamic models.

Behavioural numerical models do not attempt to represent the individual processes in detail but instead use some form of time-averaged parameterization of the processes and overall system state, often being used to address system changes over medium to long time periods (months to decades or longer). They range in complexity from simple models which require limited computation time to complex or otherwise computationally demanding models with numerous time steps in which the morphology is progressive updated.

All numerical models depend, to some degree, on data, but can also add to the information value of collected data by allowing extrapolation beyond the temporal (and spatial) scale(s) for which data are available, and by allowing alternative scenario testing to be carried out (Figure 1).

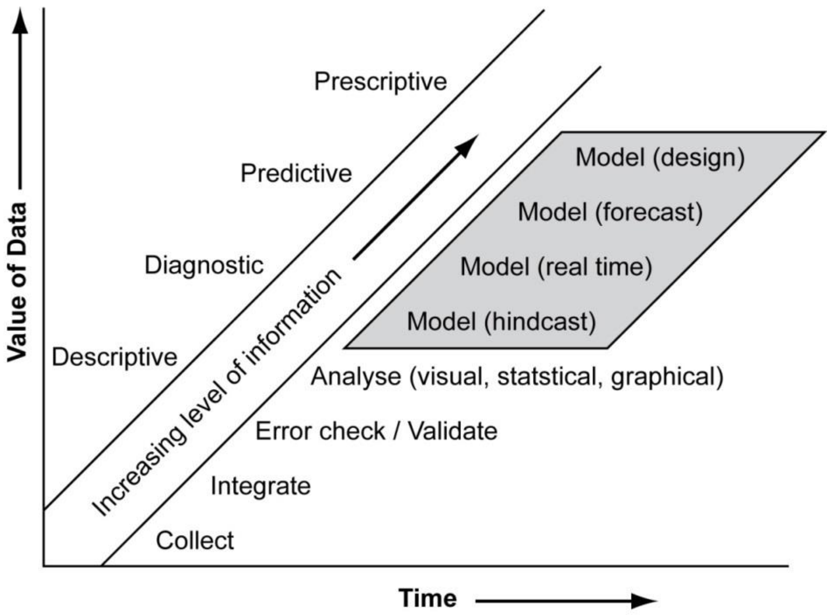

Figure 1. Schematic diagram showing how the interactive use of models and data contribute to provide increasing levels of information with increasing timescale (modified from a figure presented by S.G. Flood at the DHI UK & Ireland Symposium 2017)

3.2 Dimensionality of models

Numerical models can also be classified in terms of their dimensionality:

0D - zero dimensional or 'box' model, sometimes referred to as a 'lumped parameter' model, where an attribute of interest is assumed to have a uniform distribution within the space under consideration, or where only aggregate properties (e.g. total 'object' number, or total suspended sediment load) are of interest

1DH - one line model, e.g. characterizing change in horizontal shoreline position or cross-shore profile

1DV - one line model providing information about vertical processes, e.g. with depth in the water column, as for example in the movement of a flood wave down the length of a river or estuary channel

2DH - information shown in plan view but with depth-averaged information (e.g. the spatial distribution of depth-average current velocity or suspended sediment concentration with an estuary or bay)

2DV - information shown in single cross-section view, e.g. an estuary cross-section or beach profile

Quasi-3D - information both in plan view and for a series of linked horizontal layers through the water column (sometimes referred to as integrated multiple layer 2DH models)

3D - a model in which the full 3D flow equations are solved; these may be further sub-divided into hydrostatic and non-hydrostatic types; the latter provides high resolution representation of turbulent flow and are often referred to as computational fluid dynamics (CFD) models.

2DH and Quasi-3D models are often referred to as ‘coastal area models’, since they can be applied to quite large geographical areas of the continental shelf and adjoining coast (e.g. Liverpool Bay or the Irish Sea). Fully 3D CFD models are generally too computationally demanding to be applied at the regional scale and are mostly used for small scale studies of the interactions between structures and turbulent flows (e.g. tidal energy turbine arrays).

This conceptual division of model types in terms of dimensionally should only be considered as a guide, since numerous intermediate model types have been developed, including ‘multi-line models (n-line models), multi-profile models (De Vriend et al, 1993), and 1.5D models which introduce redistribution of sediment within a coastal profile in response to horizontal 2DH currents, thereby allowing simulation of 2D morphological evolution (e.g. Kristensen, 2012). Models which consider change in three-dimensional space over time could more appropriately be considered as 4D models.

Increase in process-based model dimensionality and model run duration is generally associated with increase in model complexity, input and calibration/ validation requirements, and with increased run time and cost. It is also sometimes associated with increased model uncertainty since it is often difficult or impossible to provide reliable / verified input parameterization to the model at high spatial and temporal resolution.

3.3 Examples of proprietary and open-source models

A list of examples of numerical models which are now frequently used in the UK, together with a number of tools for modelling long-term coastal morphological change which have been developed in recent years, is provided in Table 2. A summary of the main model characteristics and availability is provided in Table 3. Capability summaries for selected models considered to be of particular importance are contained in Appendix 1.

Table 2. Examples of models used in the UK for environmental assessment

Model	Organisation	Website
Hydrodynamic Models		
Delft 3D	Deltares	oss.deltares.nl/web/delft3d
FVCOM	University of Massachusetts	fvcom.smast.umassd.edu/fvcom/
POM	Princeton University	www.ccpo.odu.edu/POMWEB/
NEMO	NEMO System Team	www.nemo-ocean.eu
RMA 10 / 11	Resource Modelling Associates	ikingrma.iinet.net.au/
CORMIX	MixZon Inc.	www.cormix.info/
DIVAST	Cardiff University	
TRIVAST	Cardiff University	
MIKE 11	DHI	www.mikepoweredbydhi.com
MIKE 21 FM	DHI	www.mikepoweredbydhi.com
MIKE 3 FM	DHI	www.mikepoweredbydhi.com
POLCOMS	Proudman Oceanographic Laboratory	http:/www/channelcoast.org/iCOASST/POLCOMS/
EFDC	US Environmental Protection Agency	www.epa.gov/exposure-assessment-models/efdc
TELEMAC -2D	EDF	www.opentelemac.org/
TELEMAC -3D	EDF	www.opentelemac.org/
TUFLOW FV	BMT WBM	www.tuflow.com/
OpenFOAM	OpenCFD Ltd	www.openfoam.com
Ansys-CWR	ANSYS Inc	www.ansys.com
Wave Models		
SWAN	Delft University of Technology	www.swan.tudelft.nl/
WAVEWATCH III	NOAA	polar.ncep.noaa.gov/waves/wavewatch/
FVCOM-SWAVE	University of Massachusetts	fvcom.smast.umassd.edu/fvcom/
TOMAWAC	EDF	www.opentelemac.org/
MIKE 21 SW	DHI	www.mikepoweredbydhi.com
MIKE 21 BW	DHI	www.mikepoweredbydhi.com
WAM	Helmholtz-Zentrum Geesthacht	mywave.github.io/WAM/
STWAVE	US Army Corps of Engineers	http://www.dtic.mil/dtic/tr/fulltext/u2/a550608.pdf
Inundation & Overtopping models		
SLOSH	National Weather Service	www.nhc.noaa.gov/surge/slosh.php
Lisflood_FP	University of Bristol	www.bristol.ac.uk/geography/research/hydrology/ models/lisflood/
SWAB	University of Manchester	modelling.mace.manchester.ac.uk/user/login/?next=/
SWASH	Technical University of Delft	swash.sourceforge.net/
EurOtop	HR Wallingford	www.overtopping-manual.com
TUFLOW Classic	BMT WBM	www.tuflow.com/
AMAZON-HSB	University of Manchester	www.scmdt.mmu.ac.uk/cmmfa/projects/ overtopping/amazonhbs.html
Short-term Process-based morphological evolution models		
XBeach	Deltares	oss.deltares.nl/web/xbeach/
XBeach-G	Deltares	oss.deltares.nl/web/xbeach/
CSHORE	US Army Corps of Engineers	sites.google.com/site/cshorecode
LITPACK	DHI	www.mikepoweredbydhi.com
Long-term Morphological Evolution Models		
SCAPE+	Mike Walkden, University of Bristol	www.channelcoast.org/iCOASST/SCAPE/
COVE	BGS & Glasgow University	github.com/COVE-Model
CEM	Duke University	csdms.colorado.edu/wiki/Model:CEM
UnaLinea	HR Wallingford	www.channelcoast.org/iCOASST/UNALINEA/
ASMITA	Delft University of Technology	www.coastalsea.uk/download-page/asmitaoo/
ESTEEM	University College London	www.channelcoast.org/iCOASST/ESTEEM/
COASTAL ME	Southampton University	www.channelcoast.org/iCOASST/COASTAL_ME/
MESO i	Southampton University	www.channelcoast.org/iCOASST/MESO_i/

Table 3. Model features and characteristics. Source code: O = Open, RO = Restricted Open, P = Proprietary. Sediment: NC = Non-cohesive, C = Cohesive, ST = short term)

Model	**Source Code**	**Dimensions**	**Wave forcing**	**Sediment**	**Morphology**	**Particle Tracking**	**Water Quality**
Hydrodynamic Models							
Delft 3D	O	3D	SWAN	C, NC	Y (ST)	Y	Y (DELWAQ)
FVCOM	RO	3D	SWAVE	C, NC	Y (ST)	Y	Y
POM	O	3D	Y	N	N	N	N
NEMO	RO	3D	Y	N	N	Y	Y
RMA 10 / 11	RO	3D	Y	C, NC	Y (ST)	Y	Y
CORMIX	P	1D, 2D	N	N	N	N	Y
DIVAST	O	2D	N	Y	N	N	Y
MIKE 11	P	1D	N	C, NC	Y (ST)	N	Y
MIKE 21 Flow Model	P	2D	MIKE 21 SW	C, NC	Y (ST)	Y	Y
MIKE 3 Flow Model	P	Q3D	MIKE 21 SW	C, NC	Y (ST)	Y	Y
POLCOMS	P	3D	WAM	NC	Y (ST)	Y	Y (ERSEM)
EFDC	O	3D	Y	C.NC	Y (ST)	Y	Y
TELEMAC -2D	O	2DH	TOMAWAC	C, NC	Y (ST)	Y	Y (DELWAQ)
TELEMAC -3D	O	3D	TOMAWAC	C, NC	Y (ST)	Y	Y (DELWAQ)
TUFLOW FV	RO	2DH, 3D	Y	C, NC	Y (ST)	Y	Y
OpenFOAM	O	3D	Y	C, NC	Y (ST)	Y	N
ANSYS CFX	P	3D	N	C, NC	Y (ST)	Y	N
Wave Models							
SWAN	O	2DH	Y	N	N	N	N
WAVEWATCH III	RO	2DH	Y	N	N	N	N
FVCOM-SWAVE	RO	2DH	Y	N	N	N	N
TOMAWAC	O	2DH	Y	N	N	N	N
MIKE 21 Spectral Waves	P	2DH	Y	N	N	N	N
WAM	O	2DH	Y	N	N	N	N
Inundation & Overtopping models							
SLOSH	RO	2DH	Y (surges)	N	N	N	N
Lisflood_FP	O	2DH	N (flow)	N	N	N	N
SWAB	RO	1DH	Y (waves)	N	N	N	N
SWASH	O	2DH	Y (waves)	N	N	N	N
EurOtop	O	1DH	Y (waves	N	N	N	N
TUFLOW Classic	RO	1DH, 2DH	N (rivers)	N	N	N	N
AMAZON-HSB	RO	1D &2D	Y (waves)	N	N	N	N
Short-term Morphological Evolution Models							
XBeach	O	1DH, 2DH	Y	NC (sand)	Y	N	N
XBeach-G	O	1DH	Y	NC (gravel)	Y	N	N
CSHORE	O	1DH, 2DH	Y	NC	Y	N	N
LITPACK	P	1DH, 1 line	Y	NC	Y	N	N
Long-term Morphological Evolution Models							
SCAPE+	O	Q3D		NC, C	Y	N	N
COVE	O	1DH, 2 line		NC, C	Y	N	N
CEM	O	1DH, 1 line		NC, C	Y	N	N
UnaLinea	O	1DH, 1 line		NC, C	Y	N	N
ASMITA	O	Q2D		NC, C	Y	N	N
ESTEEM	O	1D, 2D		NC, C	Y	N	
COASTAL ME	O	2DH, 1 line		NC, C	Y	N	
MESO i	O	Q2D		NC, C	Y	N	

3.4 Applicability and data input requirements for 1D, 2D and 3D hydrodynamic, sediment transport and water quality models

The computational basis of all numerical hydrodynamic models is provided by the Navier-Stokes equations which describe the motion of fluids. For modelling purposes in shallow seas and estuaries, where flows in the horizontal are much larger than in the vertical dimension, a simplified form of the Navier Stokes equations, the shallow water equations, is usually employed.

1D hydrodynamic models, such as MIKE11 and TUFLOW 1D, are more suited to the simulation of flows in confined channels such as rivers or urban drainage networks, and they are extensively used in fluvial flood risk modelling. 1D models have, however, also been used to model flows in narrow estuaries as a function of changing channel form, and to model the behaviour of turbidity maxima and saline intrusions at the heads of estuaries.

Tidal heights, current speed and direction are closely related and so are typically modelled at the same time using a 2DH, pseudo-3D or, more rarely, a fully 3D hydrodynamic model. In the 1980s and early 1990s, before the rapid expansion of computing power, most riverine and coastal area models used depth-averaged (2DH) models. Even within the past decade, such models (e.g. MIKE 21, TELEMAC 2D, TUFLOW 2D) have been widely used to asses both the near-field and far-field effects of, for example, tidal energy schemes and windfarms (e.g. ABPmer, 2014), or at a more local scale to assess the effects of breaches in tidal defences (e.g. Scott Wilson, 2010). This approach is often sufficient if the main topics of interest are changes in water levels, depth-averaged currents or estimated bed shear stresses which might rise from a scheme, or in the initial 'pilot modelling' phase of an assessment. However, in many situations, particularly in estuaries and bays which receive significant freshwater input, there is significant vertical variation in temperature, suspended sediment concentration as well as salinity, or where wind forcing is significant, it is important to consider the three-dimensional structure of the flows which occur (Amoudry & Souza, 2011).

In the 1980s and early 1990s 'pseudo' or 'quasi'-3D models were developed to avoid solving the full three-dimensional hydrodynamic equations (e.g. de Vriend & Ribberink, 1988; papers in Nihoul & Jamart, 1987), and such models remain widely used. Some of the most commonly used in the UK are Delft-3D, MIKE 3 and Telemac 3D. Fully 3D models, which employ full solutions to the Navier Stokes equations, are also used, although for large modelling domains this is computationally very demanding and expensive. Consequently, fully 3D high resolution flow modelling is usually restricted to small scale applications such as the flow and sediment transport patterns around tidal energy turbines and similar structures. For example, Waldman et al. (2014) assessed the flow around an array of tidal energy turbines using both the DHI MIKE3 FM HD and the ANSYS CFX TideModeller CFD modelling package, demonstrating that the latter provided much better spatial resolution of wake effects than the former. Lauchlan Arrowsmith & Zhu (2014) compared output from MIKE 21 HD with that from ANSYS CFX DesignModeller in a study of vertical slot fishways. Although the CFX model was found to be more time consuming and complicated to set up than the 2D MIKE 21 model, once configured the meshing algorithms in the CFX model were found to be more flexible and easier to modify for different design options than in the 2D model which required an entirely new model grid to be constructed for each design. High resolution 3D CFD models are also being increasingly used to investigate problems such as bed scour and sediment deposition around sea bed oil and gas pipelines, power station cooling water intake / discharge pipes, and similar structures). The open-source CFD model OpenFOAM has also been used recently to model flow over beaches and coastal dunes (Hesp & Smyth, 2016a, b), and has previously been used to investigate phenomena such as dam bursts and embankment breaches (e.g. Biscarini et al., 2010).

A summary of the general applicability of different hydrodynamic model types to near field and far field impact assessment, and in different coastal, estuarine and marine environments, is provided in Table 4, while Tables 5, 6, 7 and 8 summarise some of the main input data requirements for hydrodynamic tidal models, wave models, sediment transport models and water quality models, respectively.

Table 4. General applicability of different types of hydrodynamic model

Model type	Near Field	Far Field	River	Narrow estuary	Broad estuary	Bay	Open coast	Shelf area
1DH	yes	no	yes	yes	no	no	no	no
1DV	yes	no	yes	yes	no	no	no	no
2DH	yes	yes	yes	yes	yes	yes	yes	yes
2DV	yes	no	yes	yes	no	no	no	no
Q3-D	yes	yes	yes	yes	yes	yes	yes	yes
3D	yes	yes	yes	yes	yes	yes	yes	yes

Table 5. Major model input requirements for hydrodynamic (tidal) models

Model type	Domain definition	Bathymetry and grid / mesh	Start / finish times	Initial/ boundary conditions	Density (and/or temp/ salinity)	Eddy viscosity	Bed roughness	Wind/ Wave forcing	Freshwater input	CFL Number
1DH	Yes	No[1]	Yes	Yes	Yes	Yes	Yes	No	Option	Yes
1DV	Yes	No[1]	Yes	Yes	Yes	Yes	Yes	No	Option	Yes
2DH	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	Option	Yes
2DV	Yes	No	Yes	Yes	Yes	Yes	Yes	Option	Option	Yes
Q3D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	Option	Yes
3D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	Option	Yes

[1] although some form of along-channel elevation data needs to be provided

Table 6. Major model input requirements for hydrodynamic (wave) models

Model type	Domain definition	Bathymetry and grid / mesh	Start / finish times	Initial / boundary conditions	Density (or temp/ salinity)	Eddy viscosity	Bed roughness	Wind forcing	Freshwater input	CFL Number
1DH	Yes	No	Yes	Yes	Yes	Yes	Yes	Option	No	Yes
1DV	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Yes
2DH	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	No	Yes
2DV	Yes	No[1]	Yes	Yes	Yes	Yes	Yes	Option	No	Yes
Q3D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	No	Yes
3D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	No	Yes

[1] although some form of offshore – onshore elevation data needs to be provided

Table 7. Additional input requirements for sediment transport modules

Model type	Sediment size	Size grading	Sediment density	Sediment concentration	Critical shear stress	Bed layer thickness	Sediment Transport formula			
1DH	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
1DV	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
2DH	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
2DV	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
Q3D	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
3D	Yes	Yes	Yes	Yes	Yes	Yes	Yes			

Table 8. Additional model input requirements for water quality models

Mode l type	Domain definitio n	Bathymetr y and grid / mesh	Start / finish time s	Initial condition s	Density (and/ or temp/ salinity)	Eddy viscosit y	Bed roughnes s	Wind/ Wave forcin g	Freshwate r input	Contam . input
1DH	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Option	Yes
1DV	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Option	Yes
2DH	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	Option	Yes
2DV	Yes	No	Yes	Yes	Yes	Yes	Yes	Option	Option	Yes
Q3D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	Option	Yes
3D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Option	Option	Yes

4. Best practice in numerical modelling of coastal areas in support of EIA studies

4.1 Choice of numerical modelling approach and model set up

As noted by Cooper & Dearnaley (1996), the first stage in any potential impact investigation or other study should be an initial (scoping) assessment which defines the nature of the problem, including relevant spatial and temporal scales, and the nature of relevant source – receptor pathways. This initial assessment will provide answers to the questions ‘is modelling necessary?’, and, if not, ‘is there a requirement for further data collection and analysis for assessment can be completed?’ (Figure 2).

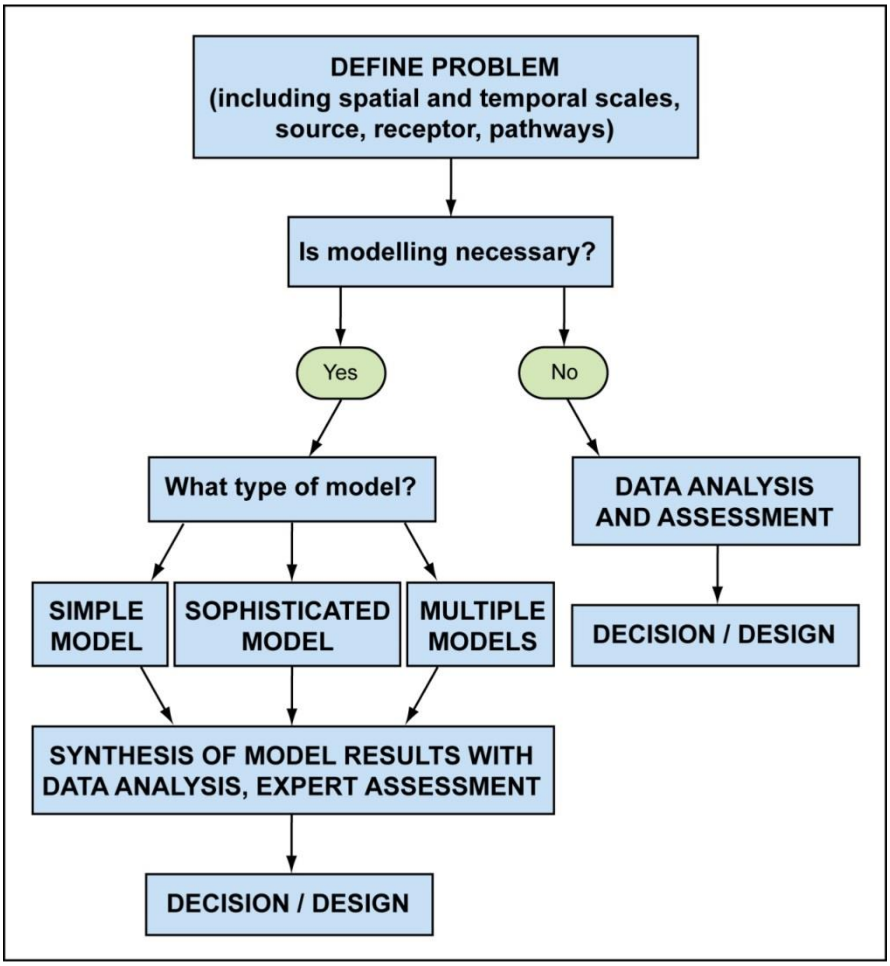

Figure 2. Illustrative stages in any potential scheme / intervention environmental impact assessment

If it is established that numerical modelling is required, and is possible (i.e. adequate resources are available and sufficient data can be obtained to allow model calibration, verification and validation), the next step is to define the modelling approach which is to be used in order to best address the questions which are being asked, and how the processes of interest are to be represented (schematized). This will include a decision whether a relatively simple model, a sophisticated model or possibly multiple models are required. Best practice requires that the numerical modelling approach selected is fit-for-purpose; i.e. it can simulate the range of processes which have been identified in the initial assessment as being important, at the required spatial and temporal scales. This may include the selection of more than one model or model type to be used at different stages of the assessment, or to address different questions which apply to different spatial and temporal scales.

The process of model selection should consider several questions:

- What model type(s) is/ are required (1D, 2D, 3D, water levels, currents, waves, sediment transport, morphology, water quality etc.)?

- What type of computational mesh would be most appropriate?

- What domain extent is required
- What temporal resolution and timescales are required?
- What boundary conditions need to be specified?
- What parameter / coefficient values need to be used?
- Are the necessary input data (e.g. bathymetry, forcing factors) available to allow the required modelling approach to be run?
- How should the structures or scheme intervention best be represented?

The choice of modelling approach will be heavily influenced by the type of scheme under consideration, including its size and the likely geographical extent of the possible impacts. Examples of typical model requirements for three different scales of scheme / intervention are provided in Appendix 2.

Most proposed development schemes proceed by way of series of stages, including pre-feasibility assessment, full feasibility assessment, initial design stage, environmental impact assessment, final design stage, construction stage, operational stage, and (sometimes) decommissioning stage. It is entirely in accordance with good practice to use different models, or different applications of models, at each stage of the process. Following the initial desk studies and review of available information, it is common practice to undertake a 'pilot' modelling study to 'scope' the general issues of relevance, and to help define requirements for further investigation and/or data collection. For typical coastal engineering or energy infrastructure schemes it is common practice to use a regional scale 2DH model for this purpose. As the scheme proceeds to full environmental impact assessment, it may be necessary to use other 2D or 3D models with greater spatial and/ or depth resolution. For example, for the purposes of the Severn Tidal Power Feasibility Study (STPFS) Strategic Environmental Assessment (SEA), only 2D modelling was used to examine the potential effects on hydrodynamics and sediment transport although it was recommended that if the project was to be taken forward then 3D modelling should also be undertaken (HR Wallingford, 2010; Parsons Brinkerhoff, 2010).

Any process-based model which is used should be able to simulate the relevant processes with sufficient accuracy to make possible meaningful comparison of the initial baseline scenario and the "with scheme" scenarios. A very large number of software packages is now available, of varying degree of complexity and with very widely varying levels of testing and validation. For EIA purposes, is important to use a well tried and tested modelling suite, and one which is designed to address the questions of interest. Commercial software packages such as MIKE software, and some open source supported software such as Delft 3D, is accompanied by detailed technical manuals and user support, together with supporting publications which provide adequate details of the model construction and the underlying equations. This is also true of some, but by no means all, open source 'community' models.

More complex models are not always better in any given situation. Additional processes should be considered in relation to their relevance to a study and the data available to accurately implement them. Increased complexity enables resolution of more processes reducing the need for parameterisations. However, complexity brings with it more choice, and potentially uncertainty, regarding the selection of appropriate model set-up parameters, some of which may be of no practical relevance, or worse introduce additional error, into the model outputs. Use of complex models will also involve greater run times and cost, reducing the scope for extensive sensitivity testing and consideration of different model scenarios.

The vast majority of models employ simplification (discretization) of the governing equations to some extent. Any output will therefore be an approximation of the full equation solutions, which themselves are a simplified representation of the often complex processes which operate in nature. Interactions between different processes, which often vary significantly both in time and space, are especially difficult to represent fully using mathematical equations.

It should be expected that the model set-up report (or reports) should provide justification for the choice of model(s) used, including alternatives considered and reasons for the preferred option(s). If it is concluded from the scoping assessment that no modelling is required / possible, the justification for this conclusion should be stated in the main environment impact assessment report (and in any scoping or preliminary environmental information reports which precede it).

4.2 Specification of model domain

The required spatial extent of the modelling domain will depend partly on the phenomena under investigation and partly on the hypothesised extent of potential impacts, as determined by the data review and expert judgement in the initial scoping assessment. The limits of the model domain should be far enough away from the proposed ‘scheme’ that the boundaries of the model do not create any feedback effects which affect conditions immediately around the scheme, or compromise the boundary conditions. As a rule of thumb, environmental processes which affect a wide area (e.g. tides), and large scale developments (e.g. a large estuary barrage or large-scale array of wind or tidal turbines), will require a consideration of an extensive far field, as well as the near field. For example, previous numerical modelling results, including sensitivity assessments, have shown that tidal barrages or multiple large tidal lagoons on the coast of Wales, the Southwest Peninsula or Northwest England, could potentially affect water levels as far away as Ireland, Scotland and Northern Ireland (e.g. Brammer, 2014; Zhou et al., 2014). Both previous modelling results and expert judgement suggest that medium-to large scale wind farm or tidal turbine array project, (10 km x 10km or greater) would be unlikely to affect water levels or currents on this scale, but could have a significant effect on waves, currents, sediment transport and the sea bed over areas extending several km away from the development.

Relatively small scale developments, such as a new detached coastal defence offshore breakwater or temporary landing facility, are unlikely to have any detectable effect on water levels or waves within an extensive far field, but near-field effects could be very significant. There may also be significant effects on longshore sediment transport along adjoining shorelines, extending tens of km from the scheme location (mainly, but not exclusively, in the net down-drift direction). It is important that the boundaries of the model domain(s) are clearly specified and justified in the model set-up report. Examples of likely modelling requirements for three example schemes of differing scale are provided in Appendix 2.

For proposed large scale projects, which could have significant far-field effects, the initial model domain should be large enough to cover the entire area where such effects might be seen. A number of different model runs with varying domains should be undertaken as part of the assessment. For example, Zhou et al. (2014), in assessing the potential impacts of a tidal energy barrage in the Severn Estuary, used a model domain which covered the whole of the Bristol Channel Southwest Approaches, the Irish Sea and the NE Atlantic off southwest Scotland. The modelling (undertaken using the EPA model EFDC_B) indicated potentially significant impacts in terms of increased high tidal levels (up to 20 cm higher) in macrotidal estuaries as far away as the outer Clyde estuary (Figure 3). Two versions of the model with different domains were employed, a Continental Shelf model and a smaller scale Irish Sea model whose boundary conditions were driven by output from the former.

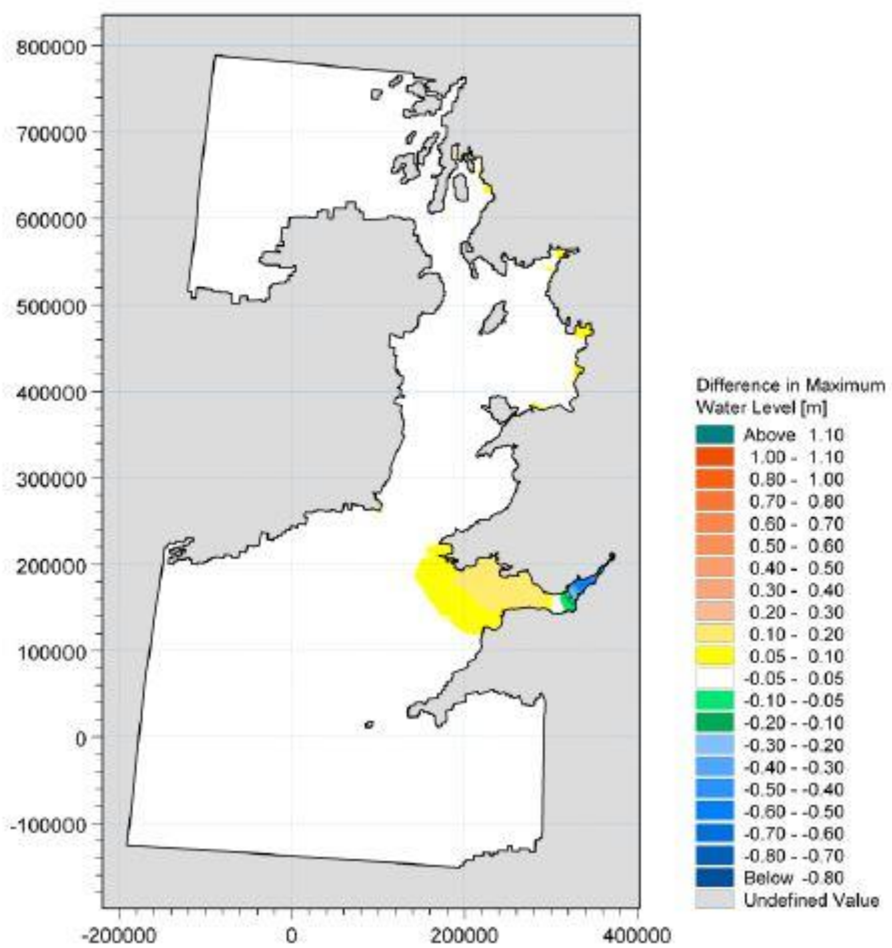

Figure 3. Predicted far field effects on maximum water level arising from a tidal barrage in the Severn estuary, obtained using the EFDC hydrodynamic model (after Zhou et al., 2014)

4.3 Choice of modelling mesh

The specification of model grid, or mesh, can be of critical importance in influencing the resolution of the results obtained. Depending on which modelling software is selected, a number of horizontal mesh types may be selected, including:

- Regular or Cartesian structured grids, which consist of elements which are square or rectangular in shape (Figure 4a)
- Rectilinear structured grids, consisting of rectangles or parallelepipeds which are not all congruent with each other (Figure 4b)
- Curvilinear structured grids, in which the cells consist of quadrilaterals rather than rectangles or rectangular parallelipepeds (Figure 4c)
- Unstructured grids (flexible meshes), which consist of interlocking cells of various shapes and sizes (commonly triangles, but also quadrangles or polygons) (Figure 4d)

Models which use structured grids are sometimes referred to a finite difference (FD) models, and those which use flexible meshes as fine element (FE) or finite volume (FV) models, depending on the mathematics employed.

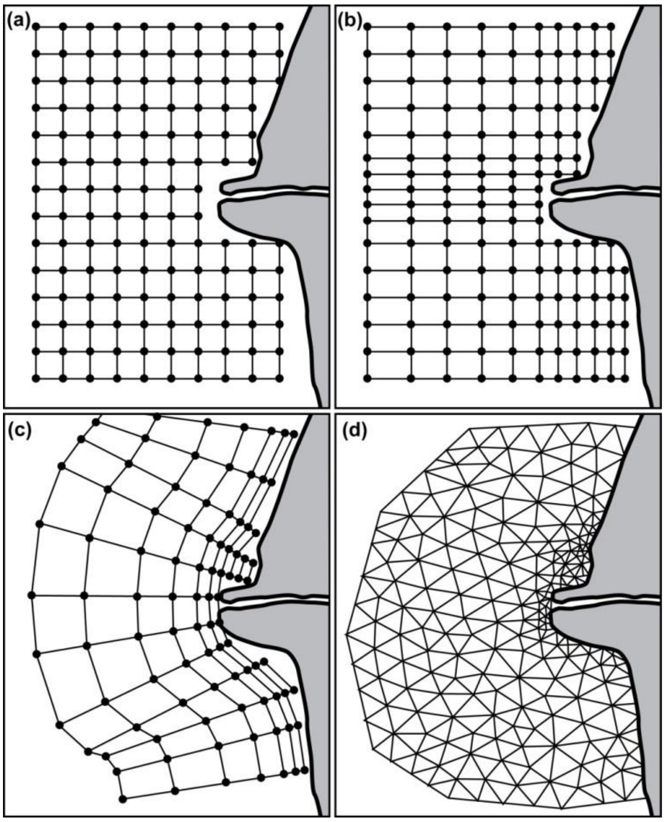

Figure 4. Examples of different types of gridding: (a) structured uniform grid; (b) structured rectilinear grid; (c) structured irregular (curvilinear) grid; (d) unstructured irregular grid (flexible mesh).

The resolution of structured grids can be varied across the modelling domain by ‘nesting’ areas of finer grid within or alongside areas of coarser grid. The resolution of curvilinear grids can also be varied spatially within the model domain. However, the greatest flexibility is provided by the use of flexible meshes. The size of the elements in the mesh can be varied according to the level of detail considered necessary to represent significant morphological features and structures, and usually increases in the coastwise direction or around a nearshore region of interest. The density and arrangement of the model mesh can be selected using options within the modelling software.

Where the model domain extends from areas of relatively deep water offshore to shallow inshore areas or estuaries, it is common practice to employ a flexible mesh with increasing resolution towards the shore, and around notable features such as headlands or structures. This allows both far-field and near-field effects to considered in adequate detail. If potential far-field impacts are of major concern, near-field processes are less important and can be simplified for computational efficiency, but if near-field impacts are of particular concern (e.g. bed scour around a series of bridge piers, windfarm monopoles or tidal energy turbines), the requirement for detailed information often means that it is only practical to model a relatively small domain (e.g. in most CFD modelling). Mesh generators usually allow manual editing of the mesh to allow smoothing (degraded resolution) in areas of lower interest around the periphery of the model domain, or to increase the resolution around structures and other small-scale features of interest.

‘Pilot’ model runs, carried out as a preliminary stage to assess the potential data requirements and model sensitivity before detailed model building and validation is undertaken, may use a low resolution mesh with relatively few nodes in order to speed up the model runs. However, a higher resolution mesh, requiring longer computation time, should be used in later runs to produce results for use in the EIA.

In the case of 3D models, a number of different vertical layer arrangements can be employed, depending on the model chosen. These include:

- Z-layers, in which the water column is divided into a number of horizontal layers of constant depth
- Sigma-layers, in which the water column is divided into a number of layers which each represent a specified proportion of the water column
- Hybrid Z layers and sigma layers

The greatest flexibility is provided by hybrid Z- and sigma layers, combined with a flexible mesh (FM).

Once the available bathymetric information has been compiled, referred to a common datum, and the model mesh selected, the bathymetric (water depth below datum) data needs to be interpolated across the mesh using options (within MikeZero in the case of MIKE software - see example in Appendix 3). The resolution and quality of

the model bathymetric grid can only be as good as the available survey data and the resolution (degree of generalization) inherent in the model mesh.
If the original survey data are of low resolution or out of date, or the chosen mesh has inappropriate resolution, the bathymetric model will provide a poor representation of the actual situation prevailing.

Figure 5 provides an illustration of the translation of composite bathymetry to a Telemac mesh of the Alde-Ore estuary). The original bathymetric data was supplied in the form of a 1 m regular grid, derived principally from intertidal LiDAR surveys and sub-tidal single beam and multi-beam acoustic surveys. These data were interpolated onto finite element model mesh nodes using an inverse weighting function of the four data values closest to each node. This resulted in some smoothing of the bathymetry but generally retained sharp features such as channel edges. The maximum size of individual elements in this case ranged from 5m in the channels to 22 m over the higher tidal flats, resulting in a total of more than 100,000 triangular elements.

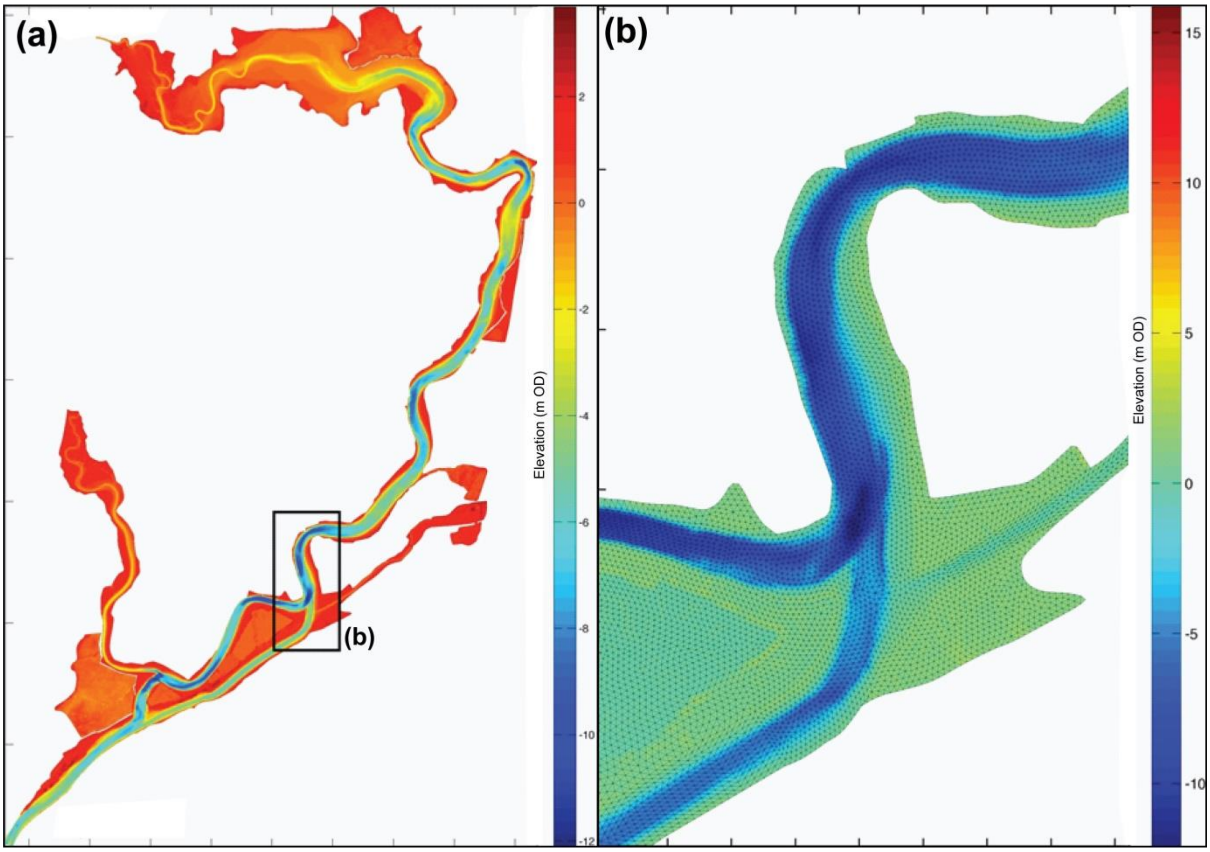

Figure 5(a) simplified bathymetry of the estuary used for Telemac2D modelling of the Alde-Ore estuary; (b) example showing the high-resolution mesh used to represent channel areas around the confluence of the Butley River and the Ore (from Pye & Blott 2015 and Pye et al., 2015)

It is of critical importance that the model mesh resolution is sufficiently detailed to represent identified features of interest and their likely interaction with tidal flows. It is good practice to undertake a number of sensitivity tests using different bathymetric meshes with different spatial resolution and different model domain boundaries, before deciding on the optimum configuration for scenario testing. A relatively coarse mesh, with elements ranging in maximum size from 12 km offshore to 20 m inshore might be sufficient to model broad-scale changes in water levels and currents, but a higher resolution is required to simulate flows and sediment transport close to the shore where features such as sand bars, channels and structures need to be represented. It is of critical importance that initial scoping assessment is sufficiently rigorous to identify any features of interest, and where appropriate, data gaps which need to be filled by new surveys before the model mesh is designed. In some situations a hierarchy of models may be required, ranging from large/scale - low resolution to small-scale / high resolution, with some being 2DH and some 3D.

4.4 Model boundary conditions

For tidal hydrodynamic modelling, open water boundaries are defined by the model extent, and input boundary conditions at the boundaries need to specified. This may be done using tidal harmonic predictions for ports or offshore locations close to the model boundary, tide gauge data for standard ports, or by taking time series of predicted water level data from a larger scale regional model. Where no tide gauge data exist for the relevant coastal area, best practice would be to calibrate the predicted input water level conditions using observational data obtained using satellite gps, over at least one spring-neap tidal cycle and for a range of meteorological conditions; however, project resourcing means that this is not always possible and in such circumstances, it is acceptable to use predicted regional model data.

For wave modelling, input data at the model boundaries are often taken from a global model or large scale regional model (e.g. those operated by NOAA or the Met Office) which incorporates both local wind conditions and swell components. Best practice would require that the model data are compared with and calibrated against measured wave data for at least one directional wave buoy within the area of interest, or at least a wave buoy which measures wave height and wind direction. For larger schemes / developments it should be expected that at least one inshore wave and current measuring systems should be installed for a minimum 30-day period in order to provide calibration and validation of modelled offshore to inshore wave transformation. However, for smaller schemes and/ or pilot assessments such deployment cannot realistically be expected, and the purpose of the modelling should be seen as quantifying the relative magnitude of change between ‘baseline’ and ‘with scheme’ scenarios.

The inshore boundary of the model is usually taken as the coastline and or tidal limit in an estuary. Any input of freshwater from rivers needs to be taken into account; in initial studies the mean daily flow is often used, but the effect of larger flood discharges may be considered as a separate calibration scenario. It is important that the nature of the coastal boundary provides an adequate representation of the real world situation, including the shape, height and composition both of any defences and the beach (if any).The model set up report should clearly state the nature of the coastal boundary conditions assumed in the model, including the nature / source of input data used.

4.5 Model parameterization

As noted above, all models require specification of the model domain, boundary conditions, start and end points, calculation and reporting time steps, and a number of other parameters which are key to the operation of the particular type of model involved. An example of the specification options available in MIKE21 software is provided in Appendix 3. Input values for many of the parameters and model options can be left blank (as zero) or other default values used, since the effect on model results may in many cases be relatively small (in the case of larger projects this should be demonstrated by sensitivity testing). However, some parameters are of particular importance and it is important to choose values which are representative of the actual range of scenarios under examination. These include the density, eddy viscosity and bed resistance (or friction coefficient). The eddy viscosity, v_t, which may be presented as separate horizontal (x,y) and vertical (z) components or as a single representative average viscosity coeficient, is used to represent the transfer of momentum due to turbulence and is non-linearly related to velocity. The density of the fluid affects its inherent 'resistance' to movement and is dependent on factors such as temperature, salinity and suspended sediment concentration; vertical and horizontal variations in density are particularly important in 3D modelling and consideration of fine grained sediment transport and water quality modelling.

Channel bed resistance is most frequently represented by a value of Manning's *n* or the Chezy coefficient, *C,* or by a friction factor such as the Nikuradse friction coefficient. Both eddy viscosity and bed resistance often vary spatially within the area of interest (river, estuary or coastal zone), and are time dependent, being related to tidal stage and water depth). Some models allow spatial variation in these parameters to be introduced via different values assigned to different mesh nodes at different time steps, but most commonly a single value is applied to the entire model domain and throughout the model run. The 'optimum' parameter values to use are usually determined through sensitivity testing to see which value gives the closest agreement between modelled and observed results. Sensitivity testing may also be undertaken by varying the conditions used in the model (e.g. river input, wave activity, Coriolis force on or off, size suspended sediment and bedload, representation of wetting and drying).

For sediment transport modelling, choices have to be made at the model set-up stage regarding how particular processes (e.g. erosion, advection/diffusion, flocculation, settling, deposition, bedload transport) are to be represented / parameterised in the model). A very large number of formulae describing these processes have been published, and choice in a particular application is often a matter of judgement which should be explained and justified in the model set up report. For example, HR Wallingford (2010), in their DELWAQ modelling investigation of mud transport in the Severn estuary related to the STPFS, characterised erosion using the Partheniades formulation, deposition calculated using the Krones equation, and flocculation represented using a simple floc model developed by Delft Hydraulics. No sensitivity tests using other formulations were reported, but the purpose of this investigation was to explore the key behaviour of the system. Other limitations imposed by the exclusion of vertical and longitudinal salinity gradients, and the use of a depth-averaged sediment transport model in an area where significant vertical variation in suspended sediment concentration within the water column is known to occur, were clearly acknowledged but the resulting uncertainties not quantified.

A useful summary of the mathematical formulation of sediment transport in coastal area sediment transport models, including boundary conditions, the bottom boundary layer, bottom roughness, bed load sediment transport, erosion and deposition of suspended sediment, sediment diffusivity, gravitational settling and flocculation, is provided by Amoudry & Souza (2011). These authors also compared five coastal area sediment transport models, CSTM-ROMS (FD-3D), Delft3D (FD-3D), ECOMSED (FD-3D), TELEMAC-SISYPHE (FE-2DH) and MIKE 3(FV-Q3D) and concluded that all have limitations. They pointed out that the most advanced model would be fully three-dimensional, would use unstructured meshes (finite volume approach) and would include a full range of processes, but no current model incorporates all these things. They concluded that, while a depth-averaged model provide acceptable results in situations where depth stratification is relatively unimportant, its failure to represent baroclinic phenonomena (depth variation) is a serious limitation in many coastal, estuarine and shallow shelf situations. The general superiority of fully 3D-FV models has also been demonstrated by other authors (e.g. Chen et al., 2003, 2007).

As part of good practice, the nature of any sensitivity tests and their outcomes should be recorded in the modelling report(s) which underpin the environmental impact assessment, and justification should be provided for the selection of the coefficient value(s) finally selected for the model application runs. It is important that values are selected which are representative of the specific area and problem under consideration.

4.6 Model verification

Model verification is the process of confirming that the model is correctly implemented with respect to the conceptual model, that the various process have been correctly represented in the model, that there are no coding errors, and that the model components interact with each other as they should; i.e. the model runs correctly, without interruptions or becoming unstable, and is generally ‘fit for purpose’ (AIAA, 1998). Various methods have been used in the process of verification, including the creation of logic flow diagrams, interactive de-bugging programmes, comparison of the behaviour of elements of the model with known test cases, and checking of the model and documented procedures by independent experts.

4.7 Model calibration

All models contain a series of constants and coefficients in the mathematical equations on which the model is based. There is potentially a very long list of such parameters depending on the model complexity (e.g. see the example listing for MIKE21 provided in Appendix 3), but the more common / important ones include the density and eddy viscosity of the fluid, the bed resistance or friction factor, the incorporation of Coriolis forcing, a wetting / drying factor for intertidal areas, and calculation time step used to ensure model stability. Several of these parameters usually have to be ‘tuned’ in order for the model to produce results similar to observed data. The process of adjusting the parameters is referred to as ‘calibration’. Uncalibrated models (referred to as pilot models) are sometime used in initial scoping studies to gauge the likely importance of potential governing factors, but only calibrated and validated models should be used to inform an EIA.

A well calibrated model should be able to produce an acceptable level of agreement between the modelled output and the observed data which it is trying to model. However, such a calibrated model may not necessarily provide a good (or ‘acceptable’) level agreement when the model is run again and compared with a second observed data set. In such instances the calibration process should be re-visited to check whether the initial acceptable level of agreement was due to chance, and/ or to identify likely sources of variation. Further tuning and model testing may be required in a series of iterative steps to obtain the best possible model performance.

There is currently no universal agreement about the criteria for numerical model calibration in the context of coastal and estuarine modelling, partly for the reason that the procedure is both model and context dependent. As such, the process is undertaken on a case by case basis, sometimes as a result of agreement between the developer / modelling consultant and the regulator. The nature of the coefficients and input parameters concerned will vary from model to model, but it is generally agreed that this process is essential.

As part of good practice, sensitivity testing should be carried out to quantify the effect of varying different model coefficients on the degree of with fit observed data. This process should be recorded and clearly reported.

Tidal water level data should be compared at 15 minute intervals against a number of observational data sets for several different locations (e.g. Class A tide gauges within the model domain), including, where necessary, tide stations established for the purpose within the primary area of interest close to the scheme.

Modelled current data should be compared with direct measurements at relevant locations within the model domain (e.g. the inner and outer parts of a Bay or estuary, or a near-field location and a far-field location). Specific metocean campaigns should be carried out to collect such data at locations most appropriate for a particular scheme, and should cover at least one, and preferably more, spring - neap-tidal cycle, in order to provide options for multiple calibration and/ or validation comparisons. Comparison should also be made with any existing longer current data sets for offshore or nearshore locations.

For wave model calibration, the model needs to be ‘tuned’ against a series of observations for wave height, wave period and wave direction. The data should relate to at least one, preferably longer, neap-tide cycles over which time the wave conditions varied significantly. As with water level and current data, the wave data should have a temporal frequency of at least 15 minutes.

For sediment transport modelling, model calibration requires suspended sediment concentration data and/ or bedload transport data over one or more tidal cycles representative of both neap tide and spring tide conditions. The instruments used to collect this data (see below) need to be carefully calibrated, often in the laboratory prior to deployment.

4.8 Model validation and quality assessment

Model validation is the process of quantifying the ability of the model to simulate real world observations. No ‘industry standard’ acceptable levels of agreement or ‘fit’ have been prescribed, partly because, as for model calibration, the definition of ‘acceptable’ is model and context dependent. However, in terms of model assessment, model validation is equally important as model calibration, for it provides, amongst other things, a measure of the true success and significance of the model calibration exercise.

Tabular and graphical comparisons of predicted and observed values provide a convenient and rapid means of quantitative assessment, and are an important first step in checking the degree of agreement or difference. Gross differences for the whole or part of a data run can be quickly identified and investigated. This step should be followed by a quantitative assessment of the ‘goodness of fit’ by determining the magnitude of the difference between simulated and observed values at each time step, and by using one or more statistical tests. Differences between simulated and observed values can be reported in several different ways, including a range of magnitude difference, percentage differences, and Root Mean Square (RMS) values.

The modelled and observed data can also be compared using a Chi-square or Kolmogorov-Smirnov test to determine a ‘goodness of fit’, or by the calculation of Brier Skill Scores (BSS, Sutherland et al., 2004) or Mean Squared Error Skill Score (MSESS, Bosboom et al., 2014). The latter are most frequently used to measure the success of a model to predict the morphological changes observed either in a laboratory flume or in a field situation. A simple t-test can also be applied to test the hypothesis that the model performance is equal to, or better than, some specified acceptable level of performance.

‘Success’ or ‘failure’ of a model should not be judged on the basis of a single test, but rather on the results of the overall assessment. Expert judgement in this process is unavoidable, since it depends on an understanding of the natural variability in the values of parameter being reported, including the potential errors associated with field measurements and the temporal and spatial variation which is to be expected in nature, and the degree of simplification inherent in the model.

ABPmer (2013a, b) suggested that, in the case of water levels, the following measures of difference over a neap-spring cycle should be calculated and reported:

- *mean surface elevation* difference (bias) over a full neap - spring tidal cycle can be calculated as the mean model value minus the mean observed value, both as a number (m) and as a percentage value of the maximum observed level

- *RMS surface elevation* difference

- *mean phase difference* (magnitude of the time difference between modelled and observed data)

For current speeds, the following should be calculated and reported:

- *mean flow speed difference* between modelled and observed flow speed, both as a number (m/s) and as a percentage of the maximum observed speed

- *RMS error of peak flow speed difference*

- *The Scatter Index*, calculated as the RMS error normalised by the mean flow speed value

ABPmer (2013b) considered that mean water level differences should be within +/- 0.2m, percentage water level differences should be within 15% of spring tidal ranges and 20% of neap tidal ranges, phase differences at high and low water should be within +/- 20 minutes, and RMS values should be < 0.2. However, a 20 cm difference in mean level could be considered large, since the implication is that the model would be unable to meaningfully assess the impact of a scheme which included a change in mean water levels of the order of 20 cm (potentially important for a change in nearshore / intertidal wave energy and mudflat / saltmarsh stability). Greater confidence can be placed in a conclusion of ‘no significant impact’ associated with a scheme if a difference in modelled and observed mean water level of < 10 cm (or < 10% difference and RMS of <0.1) is achieved, but the ability to achieve this, and its significance, will be context dependent (e.g. dependent on tidal range).

ABPmer (2013b) also suggested that modelled flow speeds should be within 0.2m/s or +/-10-20% of equivalent observed speeds, modelled flow directions should be within +/-20% of observed directions, phase difference in flow direction should be within +/- 20 minutes, RMS values should be <0.2, and Scatter Index values should be < 0.5. In practical terms, a difference of 0.2 m/s between an observed mean speed of 1 m/s and modelled speed of 0.8 m/s would be considered acceptable (subject to the other criteria being met). However, this is a relatively large difference and potentially significant when the mean flow speeds are related to bed shear stresses and potential sediment movement. The effect of the uncertainty envelope on the predicted effects should there be clearly quantified and stated in all cases.

In the case of waves, differences between modelled results and observed data can be reported in terms of:

- *mean significant wave height*

- *mean significant wave period*

- *mean wave direction*

- *Scatter Index* (RMS error, normalised by the mean value)

The opinion expressed by ABPmer (2013b) was that mean significant wave height should be within +/-10% of observed significant wave height, mean wave period should be within 20% of observed period, mean wave direction should be within +/- 30% of observed directions, and Scatter Index values for both wave height and wave period should be <35.

ABPmer (2013b) assigned qualitative descriptions of ‘goodness of fit’ based on these criteria, as follows:

Excellent fit - specified tolerances achieved >90% of the time
Very good fit - specified tolerance achieved >80% of the time
Good fit - specified tolerances achieved >70% of the time
Reasonable fit - specified tolerances achieved >60% of the time
Poor fit - specified tolerances achieved <60% of the time

Although subjective, these criteria provide a useful standard indicator which can be used to compare the outputs from different models and one assessment to another. They provide a useful and consistent yardstick which can be applied across studies, but do not necessarily provide a good measure of the model to predict specific events or conditions (e.g. extreme water levels or extreme wave heights). Additional comparisons and statistical analysis would be required to investigate the accuracy of the model(s) for such purposes.

To date, no similar criteria have been specified and generally accepted for the calibration and/ or validation of sediment transport models and water quality models. However, there is widespread consensus that as part of metocean field campaigns data should also be collected relating to bed character at the measurement point and to temporal variation in temperature, salinity and suspended concentration, and that the instruments use to obtain the field data should themselves be properly calibrated and tested in the field and/ or laboratory to determine performance efficiency (see section on data collection below).

All modelling reports should state clearly the nature of validation assessments which have been undertaken, the recorded differences between predicted and observed values for selected parameters. The procedures, for calibrating field instrumentation should be described, and the relative magnitudes of the envelopes of uncertainty associated with both modelled and observed values should be stated. Where more than one model has been used to make forecasts (e.g. a comparison of spectral wave models for coastal areas), the results obtained from each should also be compared and comment made on the origin and potential significance of differences in results obtained.

4.9 Number and length of model runs

Process-based numerical models are best suited to simulations over the short term (minutes to months) and are normally sufficient to assess ‘instantaneous’ or short term effects on water levels, current speeds, bed shear stresses and potential sediment transport arising from the introduction of a structure or ‘scheme’. Depending on the aspect being modelled, it may be sufficient to run the model for a few representative tides, or a typical neap-spring tidal cycle. A number of preliminary runs, representing a few tides, are usually used to 'spin up' the model and allow it to reach a stable condition, before results are used to characterise the 'baseline' or a 'with scheme' scenario. The model is then allowed to run for a number of further tidal cycles, the number usually being 3 to 10 if the focus of interest is water levels or currents, and several hundred or thousands if the focus is sediment transport and morphological bed change. For reasons both of model stability and computational demand, it is rarely possible to run a model in real time for more than a few weeks or months.

Morphological changes occur over time-scales far longer than those of the time-varying hydrodynamics in many coastal areas. To limit the computation times of coastal area models such as Delft3D, FVCOM, MIKE21 / MIKE3, a 'morphological factor' is frequently used implemented to estimate long-term change over periods of years or decades. This approach scales up the small morphological changes within each time step of the simulation so feedback between the bed evolution and hydrodynamics is instantaneous (Roelvink, 2006). Alternative methods, such as the use of a morphological tide (Latteux, 1995), limits the feedback to much slower (tidal) frequencies. The morphological factor simply increases the rate of change in bed elevation by a constant factor. By simulating a tidal cycle, the resulting morphological change is representative of multiple tides, determined by the value to which the factor is set (Lesser et al., 2004). This approach means that results can only be evaluated over complete tidal cycles. As an example, using a factor of 60 with a time step of 1 minute would simulate an hour every model iteration, thereby enabling a year to be simulated by considering only 12 tides. The more dynamic an area or the less linear the morphological change, the smaller the morphological factor applied. Typical values range between 10 and 1000 for dynamic to stable environments respectively (Tonnon et al., 2007).

Use of a morphological factor enables coastal morphological simulations that are often limited to short periods (typically < 1 year), due to computation times, to be run for decades. For a sandy region of fast tidal currents (<1 m/s) sand wave migration rates have been successfully simulated for a 5 year period using a 10 m grid resolution, a 15 s time step and a morphological factor of 182.5 (Tonnon et al., 2007). However, it is suggested that the scaling factor applied should be dependent on the severity of the forcing. The Bristol Channel has been used as a test site with fast tidal currents to assess if progressively smaller factors should be applied with increasing wave action (Jones et al., 2007). Morphological factors of 1, 2, 5, 10, 25, 50 and 100 were used to simulate 41 tidal cycles with no wave forcing, a 1 m 9 s wave forcing and a 2 m 9 s wave forcing. For each case, in order, the use of a morphological factor was acceptable up to the values of 10, 5 and 2 and for all cases the model stability was greatly reduced for values above 25. When simulating harbour evolution, morphological factors of 20 and 100 have been applied with a 2 minute time step for simulations at decadal time scales (Lesser et al., 2004). Here the value of erosion and deposition observations in the vicinity of a scour hole to assess the model setup and calibration has been demonstrated. For very uniform conditions, such as tides only, morphological factors have also been applied for simulations up to centuries. Such long-term simulations use morphological factors of 400 and a time step of 1 minute (Van der Wegen & Roelvink, 2008). The choice of morphological factor being assessed though a sensitivity analysis, comparing results for a range of factors (1, 10 and 400) after set time periods (e.g., 10, 100 and 200 year periods). Where a similar behaviour is seen it is considered acceptable to use the larger scaling factor. This long-term modelling approach has been used to assess the impacts of sea level rise (Dissanayake et al., 2009). However, the outputs of such modelling are, however, impossible to validate, and the effects of significant longer term changes in forcing factors and environmental controls (major changes in bathymetry, sediment supply, wave climate) are not taken into account. Given the uncertainties associated with choosing any particular morphological factor, and in applying it as a constant in time and space, only limited confidence can be placed in the forecast changes. As with many other aspects of modelling, the main value of the approach lies in sensitivity testing.

Models such as CSHORE and X-Beach are currently able to model the impact of several successive storms on beaches and dune frontages, but at present are unable to satisfactorily model recovery processes between storms. Simulation of morphological change over longer time periods cannot meaningfully be undertaken using models which resolve individual waves, tidal cycles or short term sediment transport rates, and is generally attempted using models which employ some statistical representation of the wave climate or residual sediment transport patterns.

In summary, process-based hydrodynamic and sediment transport models, including those which predict bed level or other morphological change, are most informatively run for periods ranging of a few tides (1-5 consecutive spring and/ or neap tides, following model 'spin-up') to one or more complete neap-spring tidal cycles, representative of baseline and 'with scheme scenarios. In most circumstances, only limited additional information can be gained, and assessed with any degree of confidence, from extended model runs (>1 month), with or without the use of morphological factors.

4.10 Modelling scenarios

All modelling exercises need to include modelling of a baseline scenario against which change associated with other 'with scheme' scenarios can be compared.

Several 'with scheme' scenarios may need to be modelled to evaluate the potential impact of a number of different design options (e.g. alternative locations of a tidal barrage, different locations or quantities of dredge spoil deposition). The initial 'with scheme' runs are normally use the existing (baseline) bathymetry, with some representation of the scheme structures included. Subsequent 'with scheme' model runs may also incorporate some hypothesised change to the surrounding model bathymetry arising from sediment erosion / deposition subsequent to scheme implementation.

A widely used way in which uncertainty relating to the eventual scheme design is taken into account is to use a 'Rochdale envelope' approach as outlined under the Planning Act 2008. This recognizes that the final details of scheme design may not be known at the time of EIA, but recommends that the realistic "worst case scenario", sometimes referred to a the 'Maximum Adverse Scenario" (MAS), should be evaluated in sufficient detail such that the 'main' or 'likely significant' effects on the environment can be assessed (IPC, 2011). From an EIA modelling point of view there can be considerable uncertainty in deciding exactly what this “worst case” might be, and how it should best be represented in the model. Best practice to address this issue would involve early and continuing discussions between the developer, the modelling organization, and the regulator to ensure an agreed way forward, including updating of the model results as the design evolves.

It is widely assumed that, if the realistic worst case scenario is demonstrated to have no significant impact, any other less intrusive scheme design would also have no significant impact and therefore need not be specifically modelled. A key task, therefore, is to ensure that the true “worst case” scenario, including different combinations of circumstances in addition to simple design layout, is identified and agreed between developer and regulator before the modelling is undertaken.

When modelling the effect of a proposed scheme during the operational phase or decommissioning phase, it may also be necessary to run the model with the original bathymetry modified in a number of different ways. A widely-used procedure used in relation to nationally important infrastructure projects (e.g. nuclear power stations) is to convene a panel of experts with intimate geomorphological / sedimentological / oceanographic knowledge of the area concerned in order to identify a range of credible future morphological scenarios. These are then translated into new bathymetries used in further series of model runs. The new bathymetries may also in corporate changes to the representation of structures within the model (e.g. removal of outfalls, jetties, water intakes). Scenarios may also include different future sediment budget conditions. The number of future morphological scenarios which need to be modelled will depend on the environmental context, but may, for example, include the onshore movement of a large onshore bank, a change in bank crest height, infilling of a major channel, creation of a large management realignment site adjacent to the scheme, or undertaking of a major capital dredge scheme in the approach channel to an adjacent port.

Where the combined impact of waves and tides is being considered, either in terms of water levels and coastal flood risk or sediment transport, modelling of the baseline scenario will usually require a number of different combinations to be modelled. This may include the 1 in 1 year, 1 in 20 year and 1 in 200 year estimate still water level combined with the 1 in 1 year and 1 in 20 year wave conditions from two or more directions. The same combinations of processes should be modelled for all future bathymetries. The potential effect of sea level rise over three shoreline management planning epochs (20 years, 50 years and 100 years into the future) should also be modelled. This can be represented relatively simply by raising the model water levels by an appropriate factor in accordance with the most recent published estimates (currently UKCP09, but shortly to be updated as UKCP18). A more difficult to task is to model the potential impacts of climate change on wind and wave climate, since there is much greater uncertainty associated with the magnitude and nature of future changes around the coast of Wales (and elsewhere). Changes affecting the whole wave climate, rather than just extreme wave conditions, are present much greater modelling challenge. The best approach to this issue is provided through sensitivity testing and ensemble modelling.

The number and type of scenarios which need to be modelled will depend on the size and complexity of the proposed scheme / development / intervention. As a minimum requirement where modelling has been identified as being necessary, at least two scenarios should be modelled, the present (baseline) scenario, and the immediate post-scheme scenario (i.e. with structure in place, but with no major changes in regional bathymetry, coastal morphology, sea level or wave climate). This would be applicable, for example, to assessments of small-scale channel dredging activities, groyne or breakwater construction, or to small-scale beach nourishment. At the other end of the spectrum, assessments related to nationally significant infrastructure projects (NSIPS) should include modelling of a range of future hypothetical scenarios relating to wider scale changes in bathymetry, coastal morphology, sediment supply, sea level and wind/wave climate change over time scales appropriate to the entire construction, operation and decommissioning phases of the project (this may be at least 120 years). The typical modelling requirements for three hypothetical projects of varying scale projects are discussed further in Appendix 2.

5. Establishing a physical processes baseline to support modelling

5.1 Types of data required

As noted earlier in this report, essential first stage in any project is to review and assess the available information relating to the area of interest, to develop a conceptual model of the system under evaluation, to identify potential sources, impact pathways and receptors. This will include collation and evaluation of existing data sets, results of any previous modelling, and previous interpretative reports and published scientific literature. The assessment should also identify any data gaps which need to be filled to assess potential impacts on those receptors, including data required to support any further modelling.

If the initial assessment has indicated that further modelling is necessary, data are required at three stages in the modelling process described above, i.e. initial model design, set up and verification, model calibration, and model validation. Additionally, data are required for other forms of analysis and assessment which should always be carried out in parallel with modelling, including historical trend analysis, statistical data analysis, behavioural modelling and expert geomorphological assessment (EGA). No environmental impact assessment should rely on the results of numerical modelling alone.

For hydrodynamic modelling data are required relating to:

- tidal water level data (all model types)
- tidal current speed and direction data
- freshwater input data (in the case of estuaries and some bays, all model types, but particularly important for 3D models)

- temperature data (3D models)
- salinity (3D models)
- suspended sediment concentration (3D models)
- wind forcing data (especially 3D models
- atmospheric heat flux and in some cases precipitation data (3D models)
- sea bed characterization data, including bed roughness, which is a function of bedforms, possible rock outcrops, sediment particle size, and vegetation)

For hydrodynamic wave modelling, or combined wave plus tidal current modelling, additional data requirements are:

- wave height, period and direction data at the model boundary
- wind data for the area of the model domain.

As part of best practice, measured inshore wave data should also be obtained for a point relatively close to the shore in order to allow model calibration and validation for the nearshore area. However, such data are available only for a small number of locations around the British coast, and in the case of large infrastructure projects it should be seen as a requirement to deploy at least one wave buoy, AWAC or other form of monitoring device in the adjoining nearshore zone for a period of several months, covering both 'winter' and 'summer' wave conditions. The expense of such deployment usually cannot be justified in the case of relatively small projects (e.g. smaller sea defence schemes, harbour works), but in such cases, alternative, simpler and less costly methods of acquiring nearshore wave data should be investigated (e.g. use of Argos cameras, mobile X-Band radar, wave staff / video systems) in order to provide validation checks on modelled nearshore wave predictions.

For sediment transport modelling, particle tracking modelling, short term bed evolution modelling, data relating to the following are also required for model calibration and validation, and for assessment of the modelled baseline scenario:

- suspended sediment concentrations / turbidity (data showing variation with depth in the water column are required for 3D modelling, and are desirable for 2D modelling)
- bedload sediment transport rate and directions
- particle tracer experiments
- information about sediment particle size, type and density (of both suspended and sea bed sediment).

For water quality modelling, data relating to other attributes may be required for model set-up, calibration and validation, including:

- dilute tracer dispersion
- dissolved oxygen concentrations
- ammoniacal nitrogen concentrations
- metallic contaminant concentrations
- phytoplankton abundance
- coliform concentrations

For modelling of short to medium term morphological impacts (e.g. modelling of storm impacts on beach and dune erosion), data will also be required in relation to:

- change in beach levels and morphology (e.g. position and height of ridges and runnels)
- change in position of dune toe, cliff line, saltmarsh edge etc.
- change in the height / width of shingle ridges, dunes or other features of interest.

For modelling of medium to longer term morphological impacts (months to decades), information will also be required relating to sediment budgets (beach and dune sediment volume change). This can be obtained by analysis and comparison of different epochs of beach and nearshore topographic / bathymetric survey data using GIS software.

In order to assess the effect of any proposed scheme or development compared with the baseline situation, information is also required about the location, size and nature of the development itself. In the early stages of a development proposal a number of alternative design options may be considered, and it is common for the design to evolve over time. Although it is common practice for EIA studies to deal with uncertainties in design using a 'Rochdale envelope' approach, under which the anticipated realistic "worst case scenario" is modelled and an assumption made that any other set of conditions would result in a smaller residual effect, best practice should require that the final design scenario is also modelled so that the actual residual effects can be more accurately quantified and taken into account in the design of a post-construction environmental monitoring and management plan.

There is a close dependence between the accuracy and reliability of numerical process-based model predictions and the quality and quantity of supporting data used in the model development and testing process. Best practice should therefore ensure that:

- a thorough investigation is undertaken to identify all available data sources

- any existing data used in model development and testing are supported by adequate metadata (data source, location, time, instrument used, data quality assurance processes etc.)

- if necessary, a field campaign is carried out to fill any gaps and/ or provide more up to date information

- the data used give reasonable / good coverage of the model domain

- the period of data run is sufficient, i.e. covers at least one, and preferably two neap-spring tidal cycles, and at least two significant storm events for waves (one used for model calibration and one for model validation)

- the events / time period over which data collected are representative of typical conditions (i.e. they do not only relate to an unusual time period when waves came from an infrequent direction)

- the data have sufficient time resolution

- the accuracy of new data collected should be checked by comparison with data from existing onshore tide gauges / wave buoys or from temporary deployments

- detailed error checking exercises are undertaken for all data used in calibration and validation, including removal of suspect values.

Best practice also includes:

- seeking early advice from the regulator regarding the requirements for data collection and analysis

- detailed recording and reporting of all data collection / analysis procedures

- presentation of all relevant information in documents made available to support the EIA, HRA, WFD Assessment etc., including a bathymetric data report and a metocean data report.

The purpose of these measures is to ensure that appropriate data sets are collected and used to develop and test the model(s), that potential errors are minimised, and that there is confidence in the process on the part of the regulator and other stakeholders.

5.2 Bathymetric data requirements

Bathymetric data which have both sufficient resolution and currency (i.e. accurately represent the baseline situation at the time of modelling) are a fundamental requirement in all types of modelling, and especially in modelling of nearshore and littoral processes involving waves, sediment transport and morphological change.

For the deeper water, far-field areas of a model domain, there is less requirement for up-to-date, high resolution bathymetric data since the model mesh may have a typical element size of several kilometres. However, for nearshore areas and within estuaries, which are sometimes subject to rapid changes in banks and channels, it is important that the bathymetric data used are both up-to-date and have sufficient accuracy commensurate with the mesh element sizes being used.

Sources of bathymetric data include digitized marine charts, such as those made available commercially by Seazone (http://www.seazone.com/) and UKHO (http://www/ukho.gov.uk), swath and single beam sonar survey data available from the MEDIN website (http://aws2.caris.com/ukho) or the regional coastal monitoring programmes (e.g. http:// www.channelcoast.org). For intertidal areas, topographic / bathymetric data can be obtained from LiDAR surveys, airborne photogrammetry and ground-based beach profile surveys. Useful sources of LiDAR data include the Welsh Government Lle portal (http://lle.gov.wales/home) and the UK Government open data portal (http://environment.data.gov.uk). Ground based beach profile data for Wales can be obtained from regional Coastal Groups and Local Authorities.

The bathymetric / topographic data used in modelling need to be of sufficient resolution and currency to support the type and scale of modelling being undertaken. The best data quality three-dimensional is provided by high resolution lidar surveys (for supratidal, and sometimes shallow subtidal, areas) and spatially overlapping multi-beam swath bathymetry surveys (or subtidal areas) which have been carried out a few months or at most years prior to the modelling being undertaken.

In the case of very large scale development projects specific bathymetric / topographic surveys should be commissioned to underpin the modelling where no, or no ‘current’ surveys exist, unless it can be demonstrated that the seabed is unlikely to have changed significantly over time (i.e. the sea floor is rocky or the sediments immobile, consisting for example of relict gravel deposits or glacial till). In the case of smaller projects, or the initial feasibility assessments for larger projects, it may be acceptable to use existing data sets of varying age and resolution (e.g. digitized Admiralty charts or fair sheet data, single beam echo sounder profile data of inshore areas, beach topographic profile data, data obtained from aerial photogrammetry). However, no data should be older than approximately 20 years, unless sea bed / intertidal stability over a longer period can be demonstrated.

In many situations synoptic bathymetric / topographic survey data do not exist for the whole of the defined model domain, in which case a composite bathymetric digital elevation model (DEM) has to be constructed, sometimes based on several different surveys and survey techniques (e.g. Figure 6). In compiling such a composite DEM it is important to adjust all the data to a common datum before ‘stitching’ the data together. In this process it is not uncommon to find elevation discontinuities between different surveys, arising either from errors associated with the different survey techniques or due to the effects of actual bed change between the surveys. Using GIS software it may be possible to ‘correct; one or other set of data, and ‘merge’ the data using some form of smoothing routine. However, where there are clearly major differences and inconsistences in the merged DEM, due for example to channel movements over time, the DEM should not be used and a new synoptic bathymetric / LIDAR survey commissioned.

For the purposes of modelling, LIDAR data with 2 m grid resolution and swath bathymetric data with 4 m grid resolution is generally adequate, and higher resolution data usually need to be degraded when input to the model mesh generator. Prior to use in the model, a full error-checking process should be undertaken on each data set used, and suspect data removed where necessary.

Figure 7 illustrates a situation where virtually seamless combination of near-contemporaneous terrestrial LIDAR and marine multi-beam swath bathymetry data has been possible. However, unless the surveys have been specifically commissioned for the purpose of building a bathymetric DEM there is often a data gap between the seaward side of the LIDAR data and the landward side of the multi-beam sonar data. If the elevation difference is small (<2 m) it may be possible to interpolate between the data sets; however, significant features such as shore-parallel nearshore bars may be missed in this process, and if their presence is suspected (e.g. from observed breaking wave crests at low tide) then the data gap should be filled using other methods (e.g. using shore-mounted X-band radar data, or sonar line profiles at a spacing of 50 to 100 m perpendicular to the shore).

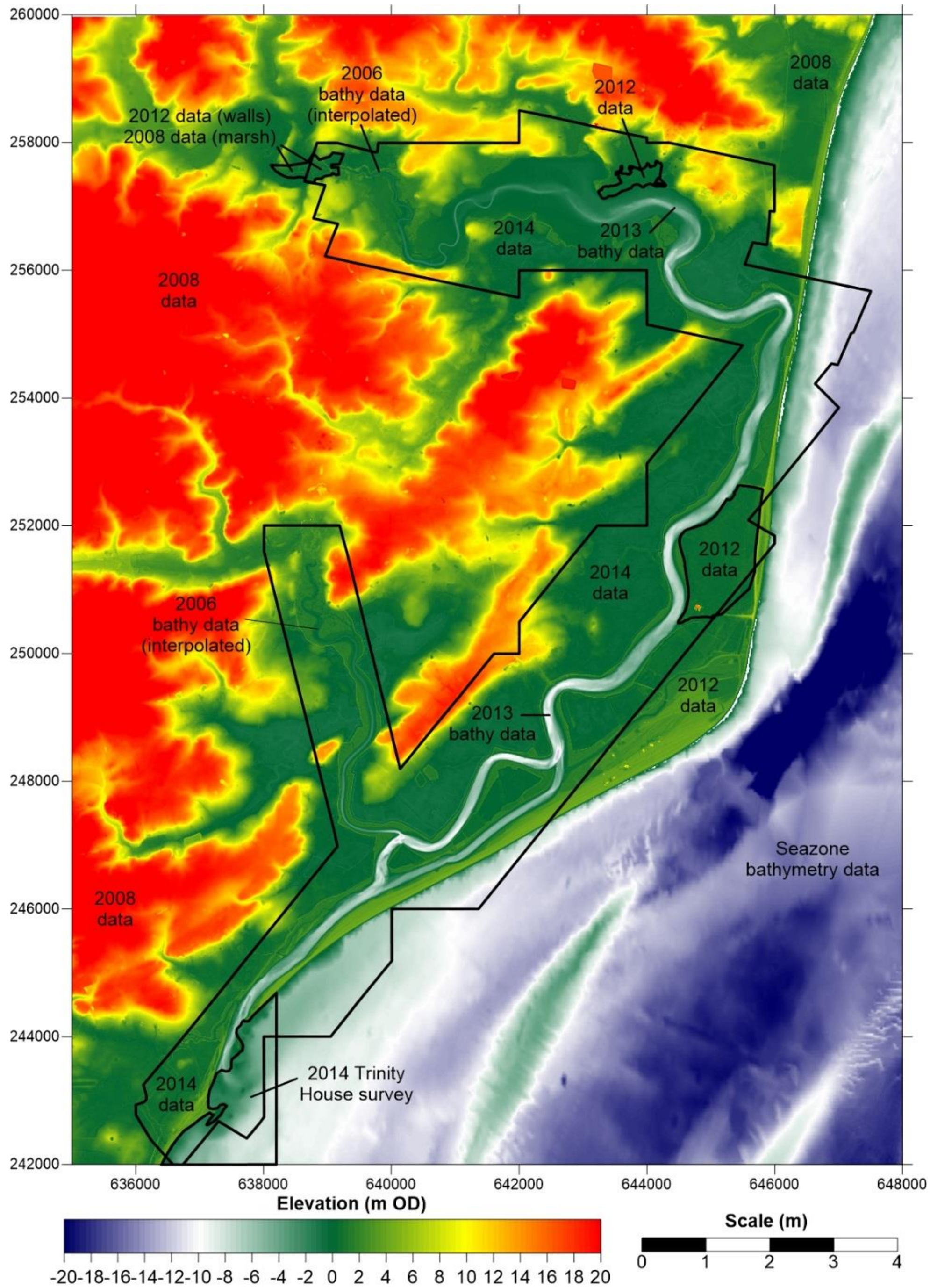

Figure 6. Example of a composite LiDAR and bathymetric DEM of the Alde-Ore Estuary, constructed using data from 2008, 2012 and 2014 LiDAR surveys, 2013 swath bathymetry, 2014 Trinity House survey of the mouth, Seazone bathymetry for the offshore area, and manually inserted bathymetry for the Butley River and upper River Alde using 2006 Environment Agency bathymetric cross-sections as a guide (source: Pye & Blott, 2015)

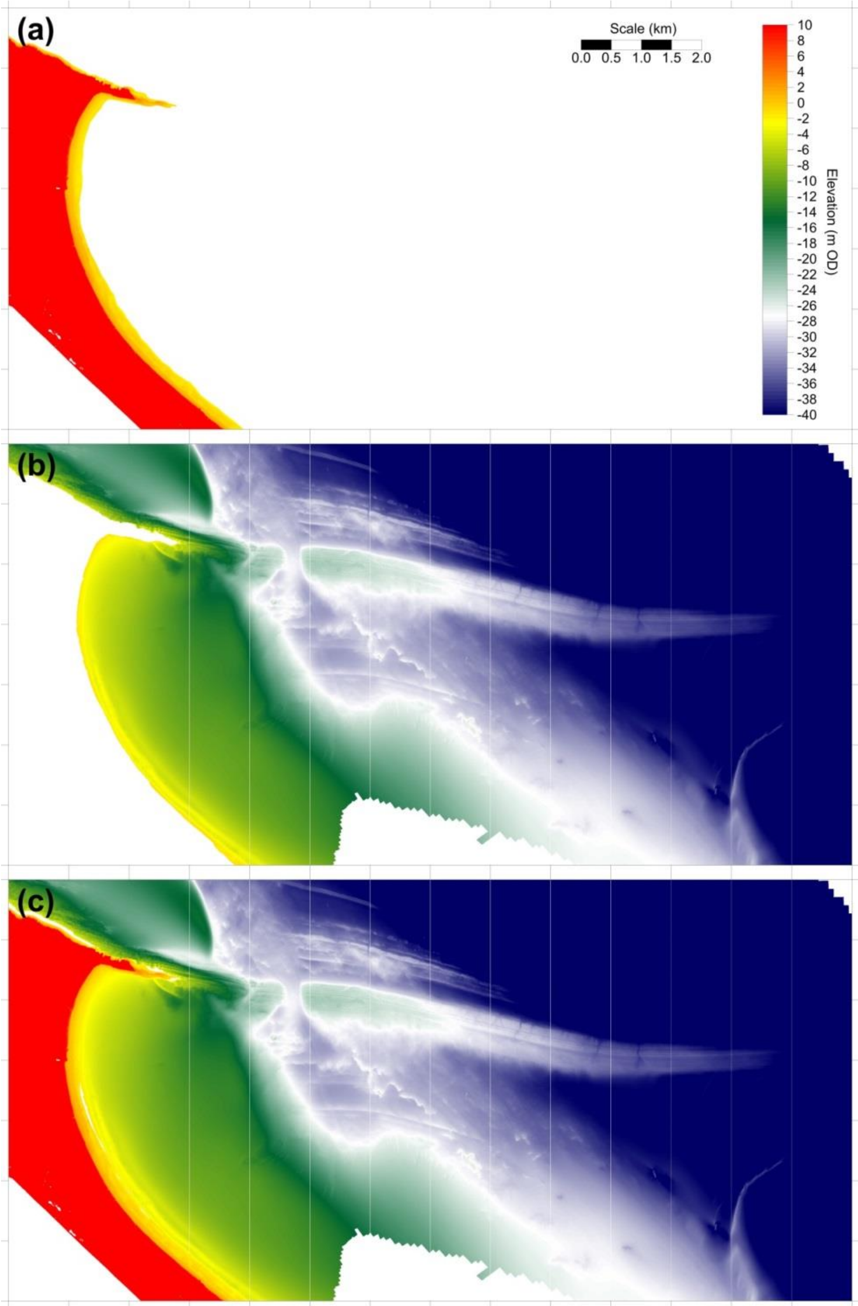

Figure 7. Example of an up-to date bathymetric - topographic DEM of the Filey Bay area produced by combining multi-beam swath bathymetric data and terrestrial LiDAR data (2016 and 2015 survey data, respectively)

5.3 Hydrodynamic data requirements

The data used to calibrate and validate a coastal hydrodynamic model should be based on measurements made every 10 or 15 minutes in order to provide sufficient temporal resolution and allow comparison with a similar time step used in the modelling. A similar time period is desirable for waves, and is required where wave – current interaction is included in modelling. The data should, as a minimum, cover a period of at least one neap – spring tidal period at a time of year when there is significant wind / wave activity (i.e. generally not in the ‘summer’ months April –

September) unless data can also be collected during the extended ‘winter’ period (October – March). Ideally, two inshore instrument deployments should be undertaken at different seasons of the year, although deployments during periods of severe ‘winter’ weather are subject to a high degree of risk. If a model is only calibrated and validated for ‘mild’ summer storm conditions, there are considerable uncertainties in extrapolating the results from the model beyond the calibration range.

For the purposes of short term modelling (up to approximately one year), data for hydrodynamic and sediment attributes are required throughout the tidal cycle, ideally at no greater than 15 minute intervals. Best practice would be to acquire data for a least two neap-spring tidal cycles (i.e. 30 days), although the greater the length of data run the better, since better sampling of natural conditions is provided. In the case of major infrastructure projects, best practice would include data campaigns lasting several months to several years.

Any data used for model calibration and validation purposes needs to be relatively recent (the more recent the better, and less than a maximum of 20 years old), and needs to be subject to a rigorous data quality assessment process before it is used. This will involve assessment of associated metadata, including information about the instrument types used and means of calibration, and examination of the data sets themselves to identify potential errors.

Tidal level data may be available from the network of Class ‘A’ tide gauges around the UK (Figure 8a), or from other gauges operated by ports or the Environment Agency where the quality of the data can be checked and verified. Recent and historical Class ‘A’ gauge data can be downloaded from the NTSLF website (http://www.ntslf.org) and longer term sea level data can be obtained from the PSMSL website (http://www.psmsl.org).

Current and recent historical wind data can be obtained for coastal stations in the UK and Ireland Figure 8b) from the UK Met Office (http://www.metoffice.gov.uk/public/weather/climate-historic/#?tab=climateHistoric) and the Irish Meteorological Service, Met Eireann (http://www.met.ie/).

Measured wave data can be obtained for wave buoys which form part of the WAVENET network managed by Cefas (https://www.cefas.co.uk/cefas-data-hub/wavenet/), for some offshore buoys operated by the UK Met Office and Irish Marine Institute and for a series of inshore buoys and other wave monitoring devices deployed for strategic coastal monitoring around the coast of England (Figure 8c & d). Much of the strategic coastal monitoring wave data can be downloaded from the Channel Coast Observatory website (http://www.channelcoast.org/).

Wave hindcast data, based on outputs form regional models operated by the UK Met Office, can also be downloaded from the WaveNet Hindcast website funded by the Environment Agency and operated by Cefas (http://wavenet.cefas.co.uk/hindcast).

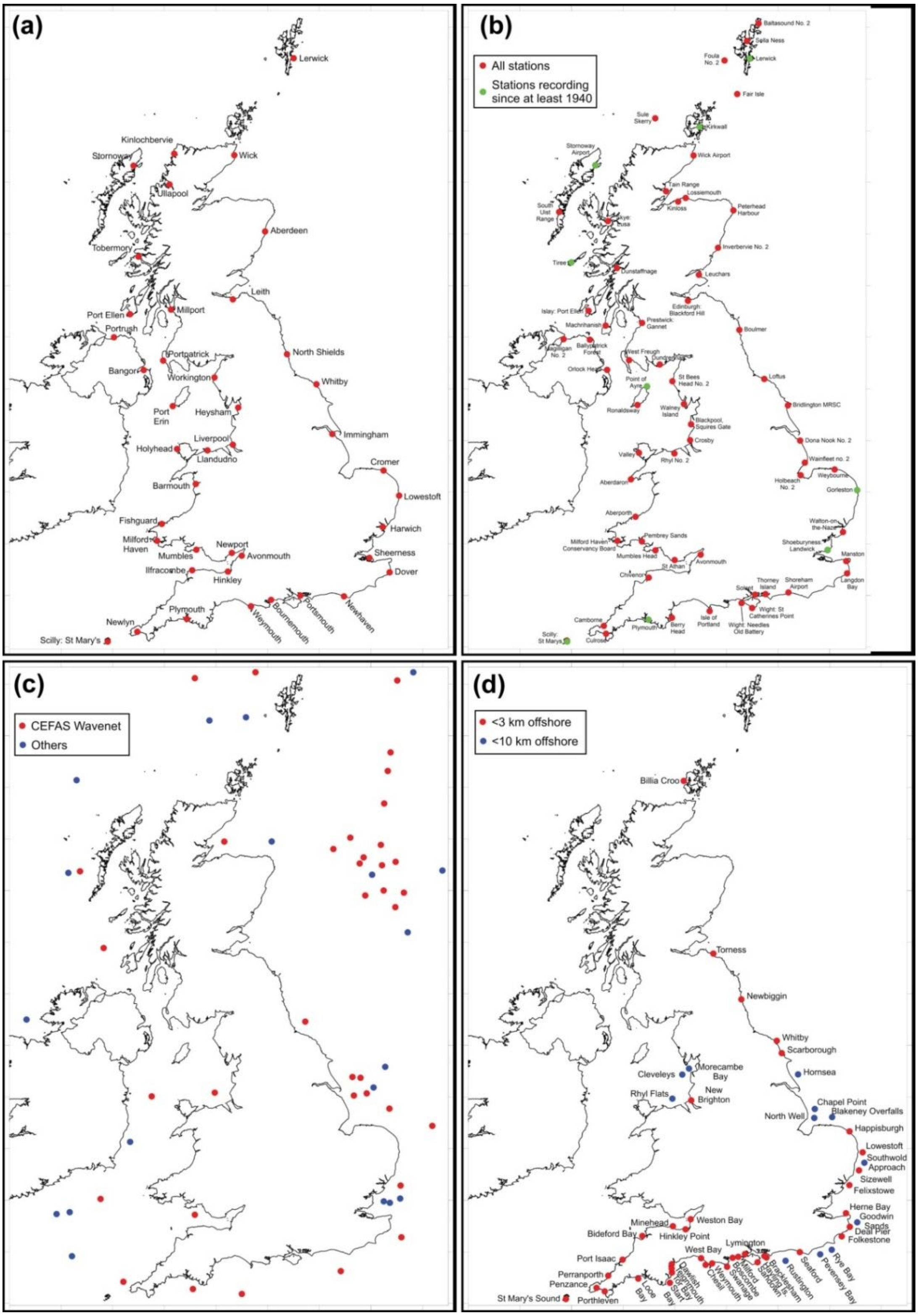

Figure 8. Locations where tide, wind and wave data are presently being obtained in the UK and adjacent waters: (a) 'Class A' tide gauge stations which form part of the BODC network; (b) UK Met Office onshore wind recording stations; (c) Offshore wave buoys (some also recording wind) and (d) inshore wave recording stations

For large coastal (and some offshore) projects, including nationally significant infrastructure projects (NSIPS), best practice would be to establish at least one 'permanent' tide gauge close to the site of the proposed development, at the start of the preliminary data gathering / modelling specification phase. This should be the case even if a 'Class A' tide gauge is located relatively nearby, since many of the Class A gauges have suffered prolonged breakdowns and suffer from major data gaps in the record. Many parts of the UK coast, including Wales, are also poorly served by Class A gauges, and some of the other gauges operated by the Environment Agency and NRW for flood warming purposes suffer from datum inaccuracies and short or incomplete records. Water levels can also be measured in conjunction with other attributes such a waves, suspended sediment concentration (turbidity), temperature, salinity) over a longer time period (target minimum of 1 year, but preferably longer if development actually occurs). A range of instrument types is available for this purposes, including wave buoys, AWAC devices and multi-instrument 'Mini-landers' which can be moored on the sea bed. The choice of appropriate instrumentation will depend on project type and scale. AWAC devices are relatively cheap to purchase and deploy and may provide sufficient information for relatively small schemes / projects, whereas Mini-landers are more complex, expensive and difficult to deploy, maintain and recover; however, they have been used to good effect to collect field data relating to a number of proposed energy infrastructure developments, including the Hinkley Point 'C' and Sizewell 'C' new nuclear power stations. Many other devices are also now available to collect metocean data at reasonable cost from shore based locations, including marine radar which can provide information about waves, currents and movement of sea bed features**.** The longer the period of instrument deployment, the greater the options for selection of representative end members of the process regime for inclusion in the modelling programme.

5.4 Sea bed characterization requirements

Models should use up to date, spatially relevant, information about the character of the sea bed in order to allow parameterisation of bed roughness and potential sediment mobility with the model. This is particularly important if sediment transport modules and bed-updating are to be used. Many models allow the median (D50), D10 and D90 of the size distribution to be specified, and at the very least allow sediment to be specified as non-cohesive (sand and coarse silt) or cohesive (mud containing a significant proportion of fine silt and clay). Surface sediments often show considerable spatial variation on the sea bed, and good practice would attempt to represent this in the model. Under best practice, data from an existing or specially commissioned sea bed sediment survey should be entered into the model via a data entry file and values translated via interpolation onto the model mesh. Acoustic backscatter surveys can be used to provided broad-scale characterization of sea bed types (rock outcrops, sand with bedforms, mud etc.), but information from such surveys should always be ground-truthed through a programme of grab sampling or coring, followed by laboratory particle size analysis. Depending on the local conditions, grab sampling may be undertaken on a regular grid system or at specified locations selected on the basis of interpretation of acoustic or multi-beam echo sounder survey data. Best practice would include sea bed sampling at an average spacing of at least 1 sample per km^2, with higher sampling densities in areas of known smaller-scale variation. Sediment sampling can often be undertaken most effectively in combination with benthic ecology and/ or geotechnical surveys, and the particle size information obtained can also be interrogated suing independent data-driven analysis methods (such as Sediment Trend Analysis). It is important that the collected samples should be large enough to be representative (a 1 litre pot, or approximately 1 .5 kg as a minimum for predominantly sandy sediments, 0.5 litre pot, or 750 g for predominantly muddy samples, and much larger samples (>5 kg for predominantly gravel sediments). The analysis should be performed at a suitably qualified sedimentological laboratory using standard procedures (e.g. those specified by the British Marine Aggregate Producers Association (Cooper & Mason, 2011), or, if the data are also to be used for biological characterization and monitoring purposes, the NMBAQC methodology (Mason, 2016). Whatever the particle size analysis methods used (sieving, laser diffraction or a combination of both), the data for the complete distribution should be reported at 'half phi' intervals and cumulative frequency percentiles (including D10, D50, D90) calculated using a programme such as Microsoft Excel. Additional summary size parameters, including modes, mean and standard deviation (sorting), can be calculated using a computer programme such as GRADISTAT (Blott & Pye, 2001). The arising data should be carefully examined in order to select the most appropriate size values to enter into the model, bearing in mind that selection of a single summary value such as the D50 may, in some circumstances, bear no relation to the sediments which are actually present on the sea bed (e.g. a bimodal muddy gravel or bimodal sandy mud).

Grab samples provide information about sediment composition immediately below the sea bed, and best practice should be also to take core samples (typically 0.5 to 10 m in length) at some or all of the sampling locations in order to characterise vertical variations with depth below the sea bed. The samples taken can also be used for the determination of geotechnical characteristics (e.g. shear strength, Atterberg Limits) or potential environmental contaminants. Information about the consolidation and shear strength of the bed sediment is important in assessing its potential mobility.

While, in most circumstances, a detailed sea bed sampling campaign cannot be justified for a small scale project (e.g. construction of an offshore breakwater for coastal defence purposes), a minimum of 30 sea bed surface grab samples should be taken and analysed to inform the baseline assessment and any modelling undertaken in connection with such schemes. In the case of medium and large-scale projects such as wind turbine arrays, tidal lagoons, port extensions etc., much larger numbers of samples should be collected (at least 100, ranging up to 1000, depending on the size and nature of the development) as part of the baseline assessment. Further surveys, perhaps involving fewer sampling locations and fewer samples, should be undertaken as part of construction phase operational phase monitoring programmes. While current practice is commonly to require scheme monitoring for periods of three of five years post-construction, best practice would also include monitoring over a longer period (potentially the entire operational phase) as frequencies of 5 to 10 years.

In some situations, sea bed surveys of physical attributes other than particle size may also be required to inform numerical modelling. This may include the extent of rock outcrops, consolidated sediment layers, vegetation (e.g. sea grass beds or algal mats) and bedform types, which can have an important local effect of critical shear stresses for sediment movement, and on local near-bed current velocities.

5.5 Sediment transport data requirements

Sediment transport data are required to calibrate and validate the sediment transport modules of the numerical models used. Wherever possible, use should be made of existing data sets identified during the initial assessment phase of the project. However, where no or insufficient data of the right quality exist, it will be necessary to collect data as part of the metocean field campaigns(s).

Many different types of instrumentation are available for the collection of suspended sediment data, including bottle samplers (pumped or otherwise), optical backscatter sensors, acoustic backscatter sensors, impact sensors, nephelometers and other forms of turbidity meters. A useful summary of methods and instrumentation is provided in the Manual of Sediment Transport Measurements in Rivers, Estuaries and Coastal Seas (van Rijn, 2007). Attributes of interest are the concentration of suspended sediment, its particle size distribution, density, propensity for flocculation and (for water quality purposes) chemical reactivity. Collection of physical samples (e.g. using bottle samplers) and laboratory analysis may be required to determine some parameters, although some attributes can be determined in the field (e.g. particle size distribution in real time using portable laser diffraction systems).

For use in 3-D models, measured data and/ or samples should be collected throughout the full water column over several tidal cycles which are representative of a range of tidal (neap / spring) and wave conditions. The number and locations of measuring points should be determined by the size of the area likely to be affected by the scheme (modelling domain), and by the environmental complexity of the area. For example, in an estuary of medium size (length 30 km) data may be required at an average of 3 km spacing along the length of the estuary, and along at least three profiles across the estuary near the mouth, in the mid estuary, and near the head.

For calibration and validation of bed-load modelling results, a number of different bed samplers are available, including the widely used Helley-Smith sampler, which is applicable for sediment sizes ranging from 0.5 to 16 mm, and the Delft Nile bed load and suspended load sampler, which can collect across the full range of sizes up to medium gravel (see van Rijn, 2007, for full descriptions and alternatives). Bedload trap samplers are only really suitable for short deployments because the traps can fill relatively quickly, and the presence of the trap and its mounting frame can cause bed scour or otherwise modify the sediment transport processes taking place. Alternative methods for longer term measurement are various types of weir trap, acoustic monitoring of bedform migration, and photographic monitoring. All measurement methods are subject to high temporal and spatial variability which needs to be taken into account when making comparisons with modelled data.

6. Error, uncertainty and confidence in model results

A significant distinction can be made between model 'error' and model 'uncertainty' (AIAA, 1998). 'Error' can be described as a recognisable deficiency that is not due to lack of knowledge, where 'uncertainty' is a potential deficiency that is due to lack of knowledge. These concepts apply as much to overall EIA process as to numerical modelling. Whereas it may be possible to estimate the magnitude of error (by statistical means or otherwise), uncertainty is much more difficult, and potentially impossible, to quantify.

The degree of confidence which can be placed in model results for the potential impact of a scheme is dependent to a high degree on the confidence that can be placed on the ability of the model to accurately represent the baseline conditions. This in turn, depends on such factors as:

- whether evidence has been provided that up-to date, representative bathymetry has been used to construct the model bathymetric grid
- whether a suitable, tried and tested model has been used, including appropriate dimensionality (1D, 2D, 3D)
- whether the modelling has been undertaken by suitably experienced personnel
- whether the domain extent and model grid / mesh selected are appropriate
- the confidence is the currency / quality of the supporting data used for calibration and validation
- the degree of successful validation of the model
- whether sensitivity testing has been carried out to determine the effect of changing model parameter values
- the degree to which the data assessment and modelling procedures have been carefully recorded an clearly presented in supporting Data and Modelling reports
- whether more than one model has been used and the results compared
- whether the modelling process and outputs have been subject to expert panel review
- how the modelling results compare with outputs from other assessment methods, such as physical modelling, tracer studies, data-driven methods such as historical trend analysis (HTA), statistical modelling, and expert geomorphological assessment (EGA).

The level of confidence which can be placed in the results of modelling of the “with scheme” scenario is also likely to be affected by confidence in:

- the way in which structures and arrangement of the scheme have been represented in the model, including consideration of uncertainty in the eventual design
- the range and nature of scenarios of future environmental change which have been considered in combination with the proposed development (e.g. natural bathymetric change, change in sea level and wind/wave climate, ‘in combination’ other human activities such as dredging, aggregate extraction, coastal and estuarine managed realignment or other onshore and offshore developments

- the extent to which natural and historical analogues have been examined (e.g. the results of monitoring the impacts of previous similar schemes.

Results from both baseline and with-scheme modelling will inevitably contain a degree of residual error associated with the quality of supporting data, and the ability of the model to present the significant processes. Predicted and actual impacts may also vary due to unforeseen, or underestimated, changes over time in environmental factors unrelated to the scheme (including ‘known unknowns’ and ‘unknown unknowns’). Best Practice requires, where possible, to quantify the residual error on uncertainty and to draw up procedures to manage it. This should include consideration of other sources of information and assessment techniques (see below) and the establishment of a monitoring framework which covers the construction, operation and potentially the decommissioning phases of the scheme, and which the underpins a Construction Environmental Management Plan (CEMP), an Adaptive Operational Management Plan (AOEMP), and potentially a De-Commissioning Management Plan (DMP). These plans should include provision for additional modelling if monitoring identifies a potentially significant change beyond the scale of impacts predicted in the EIA. The prime function of the monitoring programmes implemented should not be seen only as validating the predictions made in the EIA, but also to identify any unexpected changes at an early stage so that appropriate mitigation and / or remediation measures can be put in place before the consequences of unexpected change become serious and/ or irreversible.

7. Combining numerical modelling results with other methods of assessment

Both the residual error associated with numerical modelling, and with the overall EIA process as a whole, can be minimised if modelling is used as part of a wider process of *Integrated Assessment* which combines the results from several different lines of approach, including modelling and data analysis. At each stage of the assessment process, there should be interaction between the two assessment approaches, as shown in Figures 1 and 9. The results from each form of assessment can be compared with others for consistency (or lack of it), and apparent contradictions identified and investigated further. As noted earlier in this report, process-based numerical models are best suited to the assessment of instantaneous or short term impacts but are much less useful and reliable when it comes to predicting medium and long-term effects, such as changes in sediment budgets and morphology. The use of morphological factors to 'speed up' process-based numerical models to allow predictions over periods of several years or decades may provide an indication of potential additive consequences, but is largely an un-validated procedure.

Behavioural numerical models, of which several examples are listed in Tables 2 & 3, can be used to complement short term process-based numerical models, but the outputs depend heavily on the assumptions made and the 'accuracy' of the models is mostly un-demonstrated. Most of the models listed in Table 2 are based on highly simplified representations of natural processes but aim to provide an indication of broad scale changes over medium to longer timescales. As such they can provide a framework within which the results of shorter term process based modelling can be compared.

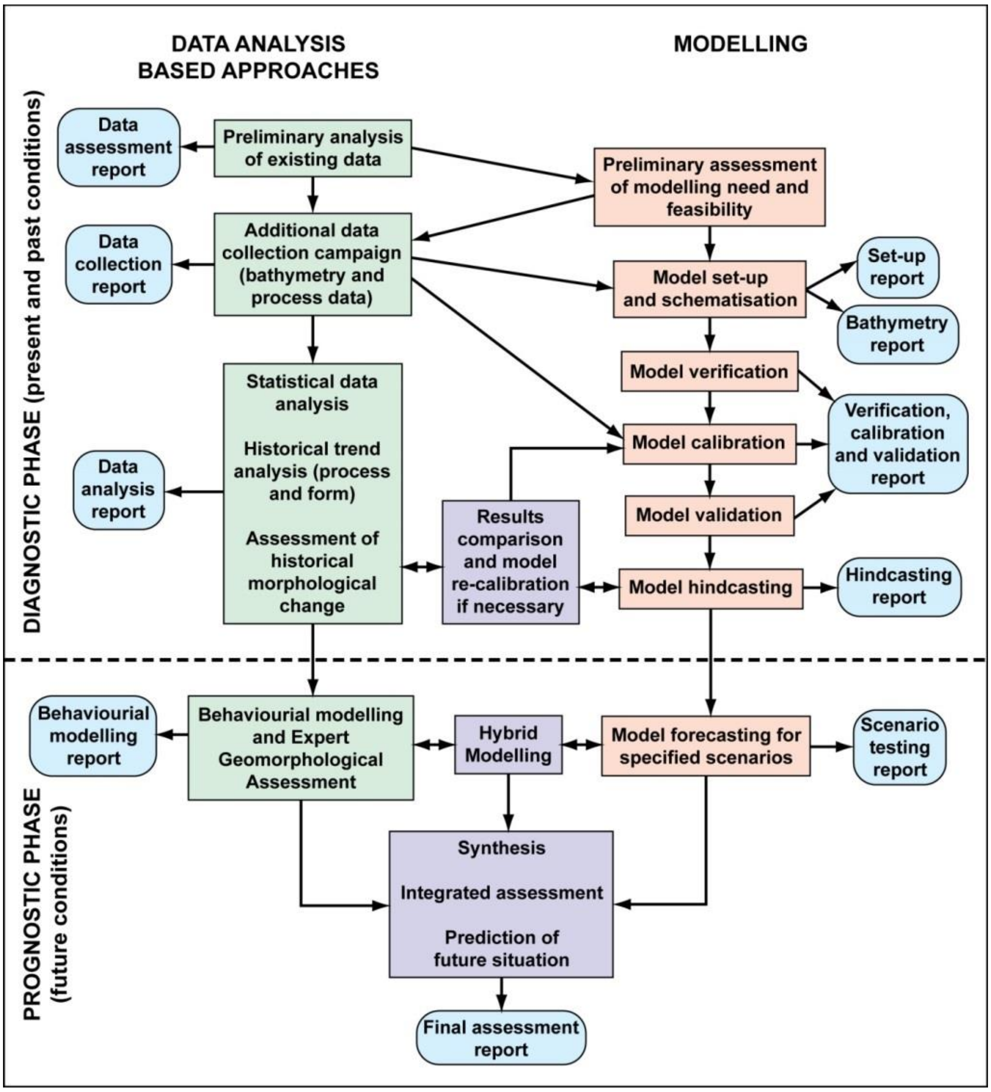

Figure 9. Summary diagram showing the complementarity of data-based approaches and modelling approaches in integrated environmental assessment (incorporating ideas from De Vriend et al., 1989)

The outputs from statistical data analysis, historical trend analysis, analysis of natural and historical analogues, and Expert Geomorphological Assessment (Pye & van der Waal, 2000; HR Wallingford et al., 2002), together with appropriately designed hybrid modelling, should all be compared with the results obtained from numerical modelling and the information synthesised to form a judgement regarding the most likely potential future situation. Possible alternative outcomes should be considered, and the level of uncertainty and risk associated with the predictions assessed. A process of Integrated Coastal Assessment, which brings together information from 'bottom-up' process-based modelling, 'top-down' numerical and data-based modelling, and expert judgement', presently offers the best method for the assessment of future change and risk associated both with human interventions and climate change (Nicholls et al., 2015).

8. Conclusions and recommendations

Based on the foregoing review of existing guidance and published literature, it is recommended that NRW should advise prospective developers and other scheme proposers that it would expect to see the following information provided in any reports and other submissions made as part of the planning and/ or licencing process:

- definition of the problem being addressed, the study objectives
- definition of a relevant source – pathway- receptor framework for investigation
- a review of the available evidence base
- justification for the decision whether or not to use modelling
- justification for the choice of any model used (ID, 2D, 3D etc.)
- technical description of the model(s), including development history, examples of previous applications and experience of the model users
- the basis for the definition of the model domain
- the basis for the type of mesh chosen
- the basis for selection of model boundary conditions
- the nature of any existing data used (bathymetry, water levels, currents, waves, sea bed characterization, sediment concentrations and particle size, water salinity, temperature and concentration of any other relevant features (phytoplankton, coliforms etc.), including their currency, spatial and temporal resolution, and procedures used to check data quality

- the nature of any new data collected, including measurement methods and procedures for data quality control

- the nature of any sensitivity tests undertake

- the basis for selection of critical model parameter values (e.g. bed roughness, bed sediment size), and method of representation in the model

- the methods used for model calibration

- the methods used for model validation and assessment of 'performance' of the model

- the magnitude of possible errors / bias in the modelling results and the potential implications for the conclusions reached

- full reference to data and metadata archiving methods, including full descriptions of the modelling procedures which can be audited by the regulator or other bodies if required.

In the case of all but very small projects, the results of the initial assessment should be presented in a Scoping Report. The nature of bathymetric and topographic data used should be presented in a Bathymetric Data Report, any environmental process data used / collected should be described in an Environmental Information Report, and any sediment data used should be described in a Sediment / Sea Bed Characterization Report. The procedures used in the design, set-up, verification, calibration and validation of the model(s) should be presented in a Model Set Up and Validation Report. The modelling results, and the interpretations made from them, should be presented in a separate Modelling Results Report. These background reports should be included as appendices to the EIA or other planning / licence application documents which contain a summary of the main aspects contained in the appendices.

In the case of small projects (e.g. small coastal defence scheme, harbour / marina improvement works) where some form of modelling has been found to be necessary it may often be sufficient to provide a summary of the relevant information as sub-sections to a single assessment report.

Where specific best practice EIA guidelines exist for particular types of development, for example offshore windfarms (CEFAS, 2004; Lambkin, 2009), or for particular types of hazard assessment such as coastal and estuarine flood risk (Johnson 2015, 2016), due account should be taken of specific recommendations.

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APPENDIX A

DESCRIPTIONS AND CAPABILITY SUMMARIES FOR SELECTED MODELS

TELEMAC-MASCARET modelling suite

TELEMAC is an open source suite of finite element modules, developed by the Laboratoire National d'Hydraulique, a department of Electricité de France's Research and Development Division. The model simulates flow, waves, sediment transport and morphology and can be applied for both river and marine studies.
The use of an unstructured grid avoids the need for model nesting within the area of interest. Space is discretised by an unstructured mesh of triangles. This allows refinement in areas of specific interest or with complex bathymetry. However, simulations are typically limited to regional scales as the time step will be limited by the smallest gird size. Model run times for a required domain will vary depending on the horizontal resolution, the number of processes included and the available computational power. Computation times of the order of a few hours would be expected for event scale simulations (lasting a few tides), while medium to long-term simulations could be in the order of days to weeks to simulate.

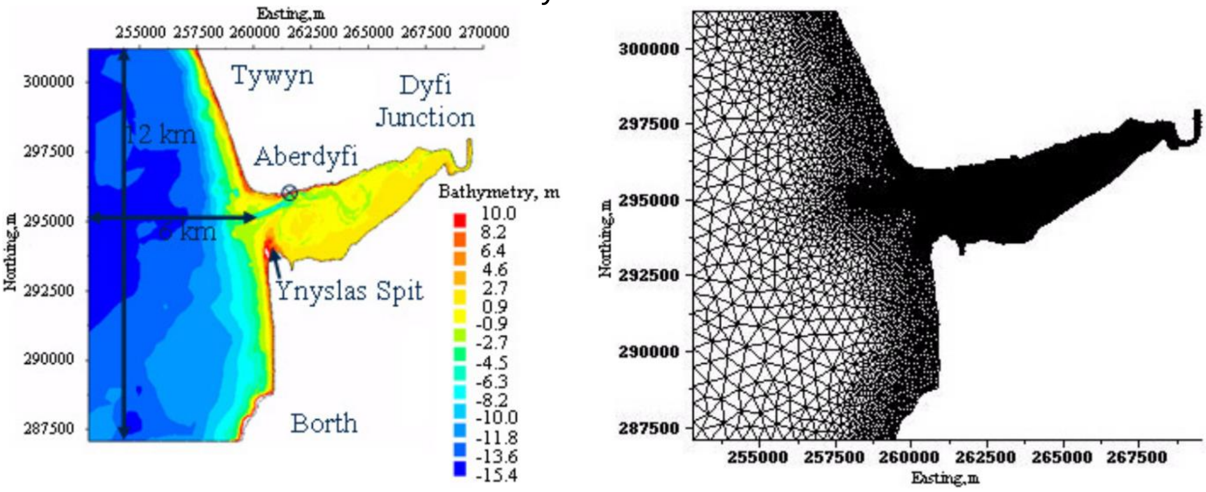


Figure A1.1. A model grid for the Dyfi Estuary developed at Bangor University (Brown & Davis, 2009). Bathymetry is relative to Ordnance Datum Newlyn

An example model domain is shown in Figure A1.1 for the Dyfi Estuary with a 20 - 100 m resolution within the estuary to resolve the channels and 500 m resolution offshore. This simulation of a tide over this domain takes approximately 30 minutes.

Hydrodynamics

TELEMAC is the hydrodynamic module, which can be applied in 2DH or 3D using a finite element or finite volume approach to simulate non-steady flow due to tidal and meteorological forcing. The 2DH version solves the Saint-Venant equations (including transport of a diluted tracer) and the 3D version solves the Navier-Stokes equations (including transport of active or passive tracers) and uses sigma - coordinates in the vertical. TELEMAC includes the propagation of long waves, taking into account non-linear effects, bed friction, Coriolis force, atmospheric pressure and wind, turbulence, torrent and river flows, horizontal temperature or salinity gradients on density, Cartesian or spherical coordinates for large domains, dry areas in the computational domain: intertidal flats and flood plains, current entrainment and diffusion of a tracer, with source and sink terms, monitoring of floats and Lagrangian drifts, treatment of singular points: sills, dikes, pipes.

MASCARET is an alternative module that simulates 1-D free surface flow (based on the Saint-Venant equations). This routine can be applied for flood inundation studies and dam breaks.

To simulate long wave propagation towards shore, and agitation into harbours over a domain of a few $km^{2,}$ the ARTEMIS module is used. This routine solves the Berkhoff's equation or Mild Slope Equation and the main outputs are significant wave height, wave incidence, orbital velocities and breaking rate. The module includes bottom refraction, diffraction by obstacles, depth induced wave breaking, bottom friction, full or partial reflections against walls, breakwaters, dikes, and radiation or free outflow conditions. Areas of application include harbour design, assessment of the impact of submerged breakwaters and groynes, flood inundation studies, discharges from outfalls, oil spill modelling.

Waves

TOMAWAC is a 3rd generation spectral wave model which can be run in conjunction with the TELEMAC flow model. It uses a finite element method to solve a simplified equation for the spectro-angular density of wave action. This is done for steady-state conditions (i.e. with a fixed depth of water throughout the simulation). The model simulates wind-generated waves and their propagation considering: refraction (by bathymetry and currents) and dissipation through bathymetric wave breaking and counter-current wave breaking. The model has been applied for engineering projects related to the design of maritime structures, sediment transport by waves, wave-current studies. Wave-current coupling can be implements such that the hydrodynamics are fed into the TOMAWAC with no return impact (flow velocity and elevation is simply updated within TOMAWAC) or there can be a two-way exchange through direct coupling of TOMAWAC with TELMAC 2D or 3D. In this case the radiation stresses are returned to TELEMAC to incorporate wave-driven flow within the hydrodynamic simulation.

Sediment transport & morphology

SISYPHE is a module that simulates sediment transport in 2D, while SEDI-3D allows for 3D suspended transport. NESTOR is a further module that can be included to include information form dredging operations within morphological simulations. SISYPHE can be applied to model complex morphodynamics processes in diverse environments, such as coastal, rivers, lakes and estuaries, for different flow rates, sediment size classes and sediment transport modes. A finite element and finite volume approach is used to simulates bedload using classical sediment transport formula and suspended load transport using a depth-averaged advection-diffusion scheme. Morphological evolution is calculated by the Exner equation. Non-cohesive, cohesive and sand-mud mixtures can be represented. The sediments are characterised by a D_{50}, grain density and settling velocity. Processes that can also be included are the effect of bottom slope, rigid beds, secondary currents and slope failure. Bed consolidation can be also be considered for cohesive sediments. SISYPHE can either be ‘chained’ to the TELMAC and TOMAWAC, where each model is run in order and outputs feed into a subsequent simulation (e.g., Brown and

Davies., 2009) or directly coupled to TELEMAC or TOMOWAC to enable feedbacks between the flow, wave field and bed updating. An additional feedback within this system is the inclusion of a bed roughness predictor (Villaret et al., 2013). Example applications of the TELEMAC suite include tidal stream resources (Guillou et al., 2016), flood vulnerability assessment (Stark et al., 2016), coast to estuary sediment transport (Luo et al., 2013), and water quality modelling (Kopmann & Markofsky, 2000; Bedri et al., 2013). Studies have been undertaken both at local (estuary) scale and at regional (e.g. Irish Sea) scales (Jones & Davies, 2006). Output from TELEMAC has also frequently been used to provide boundary conditions to other model applications, such as inundation models (e.g. Seenath et al., 2016).

For more information visit: http://www.opentelemac.org/

Delft3D Modelling suite

Delft is an open source, coupled, 3-D modelling suite available from Deltares to investigate circulation (2DH or 3D), waves, water quality, sediment transport and morphology for fluvial, estuarine and coastal environments. The model can be implemented using a regular mesh in rectilinear, curvilinear or spherical coordinates or a flexible mesh, enabling application to local coastal areas or much larger national scale problems. With the newly developed flexible mesh, a global tide-surge model has been setup (Muis et al., 2016). Model run times for a required domain will vary depending on the horizontal resolution, the number of processes included and the available computational power. Computation times of the order of a few hours would be expected for event scale simulations (lasting a few tides), while medium to long-term simulations could take of the order of days to weeks to simulate. For the regular grid applications, model nesting is often used to increase accuracy in the area of interest. Nesting can be performed in an uncoupled one-way manner, where each domain is run separately and boundary conditions are extracted from the parent domain to force a child domain, or in a coupled approach where the grids run simultaneously with two-way exchange of information across their boundaries.

An example model domain is shown in Figure A1.2 for the Severn Estuary with a coupled grid nesting in the region of the River Parrett. A serial 2-day tidal simulation for this domain takes approximately 30 minutes. The grid resolution in the parent grid varies from 460 m to 3.7 km and the child grid varies from 50 m to 825 m.

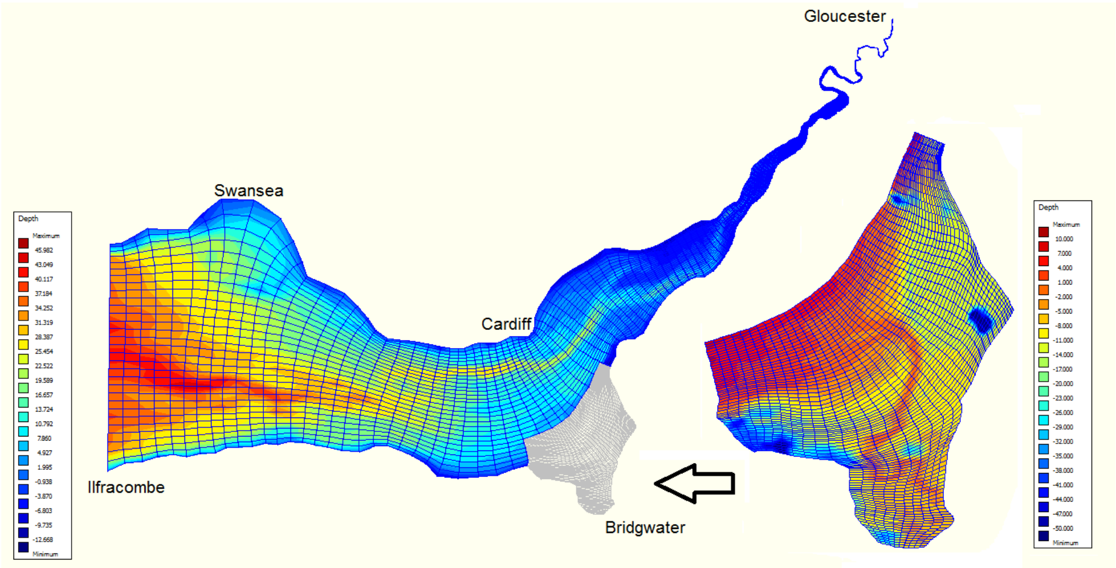


Figure A1.2. A nested model grid for the Severn Estuary developed as part of the EPSRC ARCoES project. Depth is relative to chart datum (positive values are m below CD).

Hydrodynamics

Delft3D-FLOW can be applied in 2DH or 3D to simulate non-steady flow and resulting transport (or tracks) of dissolved material or drogues due to tidal and meteorological forcing. When implemented in 3D terrain following sigma-coordinates are used. This module solves the equation of motion, and continuity equations derived from the 3- D Navier-Stokes equations for incompressible free surface flow. Key processes taken into account include:

- turbulence induced mass and momentum fluxes
- free surface gradients (barotropic effects)
- water masses with variable density (equation of state)
- horizontal density gradients in pressure (baroclinic effects)
- space and time varying atmospheric conditions on the water surface
- drying and flooding of tidal flats
- influence of waves on the bed shear-stress and mass fluxes.

Areas of application include tide and wind-driven flows (i.e. storm surges), stratified and density driven flows, river flow simulations, fresh-water river discharge into bays and estuaries, salt intrusion, cooling water intakes and waste water outfalls, transport of dissolved material and pollutants, sediment transport and morphology.

Waves

Dleft3D-WAVE enables the simulation of wind-generated waves through the 2-way coupling of Delft3D to SWAN (a 3rd generation model, Booij et al., 1999) or HISWA (a 2nd generation wave model, (Holthuijsen et al., 1989). SWAN is the default option. This 3rd generation spectral wave model computes wave propagation, wave generation by wind, non-linear wave-wave interactions and dissipation. The wave-current interactions that are considered include refraction by time-varying currents and depth, wave-setup, enhanced bottom friction, enhanced turbulence, and enhanced bed shear stress. SWAN is typically applied to domains of local or regional scale such as: estuaries, tidal inlets, lakes, barrier islands with tidal flats, channels, and coastal regions.

Sediment transport & morphology

Delft3D-SED is the sediment transport module, which can simulate cohesive or non-cohesive sediments. In the case of cohesive sediments, 'hindered settling' may be incorporated. For non-cohesive sediment (sand) both bedload and suspended load components of the transport are considered. Different sediment sizes can be specified by a D_{50} value and a bed layer thickness. For suspended sediment an initial concentration is also required. For cohesive sediments two settling velocities are required, one representing the particle fall velocity in freshwater and the second the fall velocity of the floc in water of a user defines salinity. Effects of the bed slope on magnitude and direction of transport, and effects of non-erodible layers can be taken into account. The options available typically enable studies in relation to the spreading of dredged materials, sedimentation/erosion patterns, water quality and ecology. This setup can be used for short to medium term applications (days, weeks, months), but for long-term simulations (years) Delft3D-MOR should be used to allow feedbacks between bed evolution and the hydrodynamic and wave fields to take place. A morphological scale factor can be applied to reduce computation times, but this should be applied with care. Morphological simulations can be applied to coastal areas (beaches, channels, sand bars, harbour moles, offshore breakwaters, groynes and other structures) which are intersected by tidal inlets or rivers or which flood and dry. River applications can include bars, bends (spiral flow effect), bifurcations, non-erodible layers, dredging operations, overbank flow and various structures. Estuarine applications consider the influence of tidal currents, river discharges and density currents. Sediment can be non-cohesive or cohesive. The areas may include tidal flats, channels and man-made structures, e.g. docks, jetties and land reclamations. Example applications of the coupled hydrodynamic-wave-morphological model including assessment of the Ijmuiden harbour (Lesser et al., 2004), numerous beach nourishment studies (e.g., Luijendijk et al, 2017) and the impact of offshore windfarms (McCombs et al., 2014).

Water quality

The D-Water Quality module solves a simplified representation of the advection-diffusion-reaction equation. It includes the complete natural cycles of C, N, P, Si and O_2, as well as cohesive sediments, bacteria, salinity, temperature, heavy metals and organic micro-pollutants. The module allows freedom in selecting forcing functions, which may relate to model parameters or non-modelled processes. Although algae are modelled through a Monod kinetics approach a more sophisticated algae model BLOOM II can be implemented using Delft3D-ECO, which can calculate eutrophication phenomena.

D-Water Quality can be used for Environmental Impact Assessment (EIA), water balance studies, bathing water quality assessment, sewage / storm water outfall studies; nutrient cycling and eutrophication studies, impact of dredging on water quality (Troost et al., 2014).

For more information visit: https://oss.deltares.nl/web/delft3d/about

FVCOM modelling suite

FVCOM (Finite Volume, Community Ocean Model) is an open source with limited distribution 3D coastal ocean circulation model developed by the University of Massachusetts and Woods Hole Oceanographic Institution. The model simulates flow, waves, water quality, biology, sediment transport and morphology (bed level change). It was originally developed for estuarine and coastal regions with complex geometry and steep bottom topography, which flood and dry, and has since been developed for regional shelf and global ocean basin applications (Chen et al., 2003). The original model uses a Cartesian unstructured, triangular grid and applies finite-volume approach to avoid the need for model nesting within the area of interest for regional application, while at large scale (national applications) nesting is still advised for computational efficiency. A spherical coordinate system is also available for basin and global scale applications. The vertical coordinates are terrain-following and can be a combination of sigma - and S-coordinates for shallow (shelf) and deep water applications. Model run times for a required domain will vary depending on the horizontal resolution, the number of processes included and the available computational power.

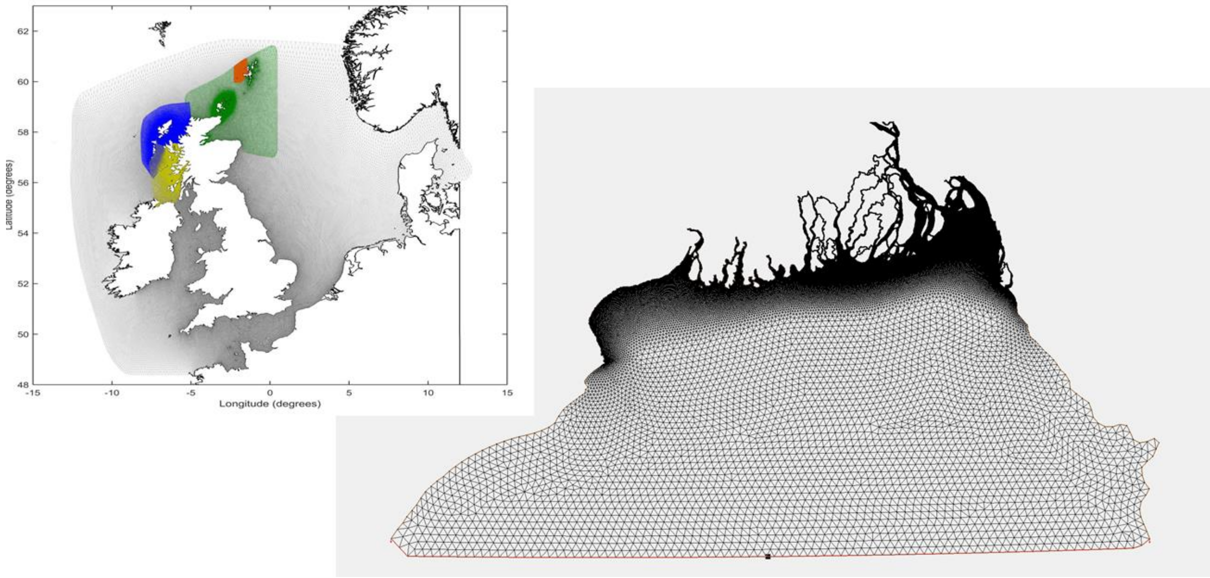


Figure A1.3. Model domains developed at NOC for the Scottish Government in a project managed by Marine Scotland Science (left) and the DFID, EPSRC and NERC funded ESPA Deltas project (right).

Computation times for an application at the UK national scale (Figure A1.3 left) takes 10 days to simulate a baroclinic model with full boundary forcing (rivers and meteorology) for a domain with 20 vertical levels and ½ million horizontal elements on a HPC using 1028 processors. A high-resolution delta application (Bangladesh, Fig. A1.3 right) takes 6 days to run a baroclinic model, with only river and open coast boundary conditions, for a domain with 10 vertical levels and 340 thousand horizontal elements on a HPC using 240 processors.

Hydrodynamics

The model simulates tidal-, buoyancy- and wind-driven circulation. It solves the 3D primitive equations to include momentum, mass continuity, temperature, salinity and density. Coupling to the Global Ocean Turbulence Model (GOTM) developed by Burchard (2002) enables the user to select different options for turbulence closure. The model includes a wetting and drying scheme for coastal regions and is fully coupled to all other modules within the suite.

Waves

SWAVE is the coupled wave module. It is a conversion of the structured SWAN (Booij et al., 1999) model to a finite-volume unstructured-grid. This 3rd generation spectral wave model solves the governing equation of the wave action density spectrum. It includes the following source & sink terms: wind-induced growth, nonlinear transfer of energy due to 3-wave & 4-wave interactions, white capping, bottom friction, depth-induced wave breaking. Wave-current coupling is performed by a two-way exchange of information considering radiation stress, bottom roughness, wave refraction, surface stress.

Sediment transport & morphology

Sediment transport and morphology is simulated using an unstructured-grid version of the USGS structured-grid community sediment model (Warner et al., 2008). Wave-current interaction is taken into consideration in the bottom boundary layer. Suspended sediment and bedload transport is simulated with the consideration of bed layers in the morphological routine. Both cohesive and non-cohesive sediment are included. Using a concentration base approach for suspended transport with erosion and deposition algorithms. Morphological evolution for the bedload component is related to gradients in the sediment transport. A morphological scaling factor can be implemented for increase computational efficiency.

Water quality and biology

A selection of water quality models are available that can be directly coupled to FVCOM or run offline using pre-simulated circulation fields. Benthic flux from sediment resuspension combined with the impact of the nutrient fluxes from the benthic layer and added to the water column creating a typical eutrophication model. As an alternative to the inbuilt options, developments at PML have also coupled

FVCOM to ERSEM (Butenschön et al., 2016) through a coupler (http://www.pml.ac.uk/Modelling/Models/Physical_models_and_couplers).
A generalized biological module is also available to simulate food web processes. This option allows users to select either a pre-built biological model (e.g., Water quality, NPZ, NPZD, NPZDB) or construct their own using the pre-refined pool of biological variables & parameterization functions. The biological module incorporates point source input from rivers, nudging at lateral boundaries, air-sea interaction at the surface and benthic flux at the bottom. This routine includes processes associated with phytoplankton, zooplankton and bacteria.

FVCOM had been used for a range of coastal ocean applications. Its flexible mesh makes it suitable for high resolution modelling of narrow estuary channels to simulate tidal salinity intrusion (Bricheno et al., 2016). Other estuarine and coastal applications have included harbour structure design, impact assessment of discharges from a sea outfall, study of thermal plumes, flood inundation studies, transport of tracers, oil spill modelling, and fish farm management. Larger scale applications have considered harmful algae bloom modelling (Aleynik et al., 2016) and offshore windfarm impact assessment (Cazenave et al., 2016). While FVCOM is often applied for specific studies, FVCOM-SWAVE (Qi et al., 2009) has also been developed as part of a coastal forecasting system. To date the model has been used much more extensively in North America than in the UK and other parts of Europe.

For more information visit: http://fvcom.smast.umassd.edu/fvcom/

DHI MIKE suite of models

MIKE software has been widely used for engineering and environmental assessments for more than 25 years (Warren & Bach, 1992). The original codes a have been extensively developed by DHI, with updates issued typically as annual releases. A range of 1D, 2D and 3D models, with numerous optional modules, is available for application to flow, sediment transport, water quality and ecological impact in rivers, lakes, urban drainage networks, groundwater, coasts, estuaries and marine environments.

MIKE 11

MIKE 11 is a 1D program which simulates flow, water level, sediment transport and water quality in rivers, canals and similar water bodies, including narrow estuaries. The HD module provides fully dynamic solutions to the complete non-linear 1D Saint Vernant equations, and can simulate hydraulic structures such as weirs, bridges and culverts. Like other MIKE software packages, the model has a Windows based user interface and can be run on a standard PC. The ST/GST module simulates the transport, erosion and deposition of graded non-cohesive sediments, and simulate changes in river morphology (bed level). The ACS module simulates the transport of cohesive sediment, including quasi-2D consideration of erosion. The ECOLAB module is used to simulate down-channel variation in Biological Oxygen Demand (BOD) / Dissolved Oxygen (D)), Nitrate, Ammonia and Heavy Metals, amongst other things. Although the basic model does not consider variations with depth in the channel cross-section, the effects of stratification in temperature or salinity can be modelled in a simple way using the Stratified Module. The FF module can be used for real time flood forecasting in rivers and the heads of estuaries. Recently the MIKE 11 software has been replaced by a number of more specialised models aimed at predicting flows within urban water networks (MIKE URBAN), rivers / river floodplains (MIKE HYDRO River), and discharges from wastewater treatment plants (WEST).

MIKE 21

MIKE 21 is a 2DH modelling package, the hydrodynamic module of which MIKE 21 HD is typically used for simulating flows in non-stratified waters, coastal flooding and storm surges, inland flooding and overland flow. Both Mike 21 and the 3D Mike 3 model (see below) are available with as a classical mesh adopting a finite difference approach (single or multiple grids) or as a flexible mesh using a finite volume approach. The software has been developed to include coupled dynamics between currents, waves and sediment transport. The suite includes a range of different packages that include the following modules: transport, particle tracking, ecology, oil spill, sand or mud transport and a spectral wave model. The model is also available in spherical coordinates making is applicable to global and regional sea scale applications.

Hydrodynamics

Unsteady flow is simulated taking into account external forcing, bathymetry and density variations. The model consists of continuity, momentum, temperature, salinity and density equations, solving the incompressible Reynolds averaged Navier-Stokes equations with assumptions for Boussinesq and hydrostatic pressure. Turbulence closure is represented by a k-ε scheme. Processes included are:

- Wetting and drying
- Momentum dispersion
- Bottom shear stress
- Coriolis force
- Wind shear stress
- Barometric pressure gradients
- Ice coverage
- Tidal potential
- Precipitation & evaporation
- Wave radiation stresses
- Sources & sinks.

Areas of application include design of port infrastructure, offshore windfarms and other renewable energy projects, and Inland and coastal flooding simulation.

Waves

A number of wave modules are available, including the spectral wave model MIKE 21 SW, and the Boussinesq wave module MIKE 21 BW. MIKE 21SW solves the wave action balance equation to simulate the growth, decay and transformation of wind-generated waves and swell. Process that are included are:

- wave growth by action of wind
- non-linear wave-wave interaction
- dissipation by white-capping
- dissipation by wave breaking
- dissipation due to bottom friction
- refraction due to depth variations
- wave-current interaction.

MIKE21BW solves the 2D Boussinesq wave equations including non-linearity and frequency dispersion. It includes many shallow water wave phenomena such as:

- shoaling
- refraction
- diffraction
- partial reflection of irregular short-crested and long-crested finite-amplitude waves wave propagation over complex bathymetries
- wave grouping
- generation of bound sub-harmonics and super-harmonics
- near-resonant triad interactions.

Areas of application include wave forecasts and hindcasts, the design and installation of offshore structures, renewable energy devices at sea and harbour, wave disturbance in ports and harbours, assessment offshore wave conditions (e.g. for oil platforms, wind farms, wave input for littoral transport and coastal morphodynamic studies.

Sediment transport, morphology and water quality

The hydrodynamic module can be coupled to non-cohesive sediment and cohesive sediment transport modules (MIKE 21ST or MIKE 21MT, respectively). An additional coupling to the wave module allows wave-current interaction to be incorporated within the sediment dynamics. Radiation stresses are transferred to simulate the wave-driven circulation. When considering sediment transport a choice of current-alone or wave-current formula are available. The options allow for bedload only, suspended load only or combined bedload and suspended load to be simulated. Bed level changes can be predicted, and morphological updating incorporated into the flow and sediment transport modules. The movement of individual particles can be simulated using a Particle Tracking (PT) module.

Coupling of the hydrodynamic model to the advection - dispersion (AD) transport module enables simulations of dissolved and suspended substances to identify their pathways (spreading and fate). This module has applications for tracer studies and assessments of flushing time and water quality. More detailed water quality assessments can be performed using the ecological module (ECOLAB), which simulates the distribution of state variable concentrations. The state variables can be described as bound to the bed, surface or sediment, or represented through the water column. It considers advective transport, biological, chemical and physical transformation processes and settling.

Areas of application include fluvial, estuarine and coastal morphodynamics, shoreline management, design optimization for harbours, marinas, beach protection structures, tidal inlet stability assessments, assessment of dredging and dredge spoil disposal, effluent discharge, assessment of wave power potential (Emmanouil et al., 2016; Jadidoleslam et al., 2016), eutrophication studies (Xu et al., 2012), integrated catchment modelling (Ma et al., 2016) simulation of morphological change around shore-parallel breakwaters (Zyserman & Johnson, 2002).The model has been proven to be particularly robust in simulating tidal flow (Zang, 2006) and has been used many in coastal situations to examine near-field through to far-field potential impacts of constructions such as harbour extensions, tidal barrages and windfarms, including the proposed Swansea Bay and Cardiff – Newport tidal lagoons.

MIKE 3

MIKE 3 is a quasi-3D free surface flow model, which also incorporates sediment or water quality processes for environmental and ecological studies. The vertical coordinate system is represented by a sigma transform approach or a combination of sigma- and z-levels (i.e. a series of integrated layers are represented within the flow). It shares many features in common with MIKE21, including a similar range of optional modules to simulate sediment transport and water quality.

For more information visit: http://www.mikepoweredbydhi.com/

TUFLOW modelling suite

TUFLOW (Two-dimensional Unsteady FLOW) is an open source inundation model with limited distribution. This free-surface hydraulics model, developed by BMT WBM, and operated in England under licence from Ch2M, simulates long waves, flood inundation and tides.

The classic model operates in 1D or 2D, while the finite volume model operates in 2D or 3D. The classic depth-averaged model is designed to simulate flow due to tides and inundation over a regular grid. The 3D model has been developed on a flexible mesh to simulate hydrodynamic, sediment transport and water quality processes in oceans, coastal waters, estuaries, rivers and floodplains. The code is optimised and parallelised for multi-processor machines to ensure efficient run times.

Hydrodynamics

TUFLOW solves the depth-averaged, momentum and continuity equations for free-surface. External forcing from wind, atmospheric pressure and atmospheric heat exchange can be included. Sub-grid scale turbulence is represented through a viscosity term. Point source inflows or outflows can be incorporated within the domain. The model is aimed at stimulating flow and inundation patterns in floodplains, coastal waters, estuaries, rivers and urban areas. The 1D solver can represent a range of different channel types in addition to open channels: circular, rectangular (box) and irregular culverts, pit or manhole inlets, bridges, weir channels (including V-notch, ogee, crump broad-crested and user-defined), spillway, radial and sluice gates, pumps, and user defined structures. The 3D flexible mesh option is a relatively new feature of the model. This option incorporates robust wetting and drying; the ability to intrinsically handle shocks; subcritical, supercritical and transitional flows; and is linked to the 1D hydraulic structure routines. This version solves the Non-Linear Shallow Water Equations. The vertical levels are represented by either sigma-coordinates or a hybrid z-coordinate. Baroclinic pressure-gradient terms can be included to simulate the response to temperature, salinity and sediment induced density gradients. A variety of options are available for simulating horizontal turbulent mixing, including the Smagorinsky scheme.

Sediment transport, morphology & water quality.

The 2DH sediment transport module is currently being replaced by the 3D finite volume model approach. For the 3D model options for both cohesive and non-cohesive sediment is included. The model being able to handle both bedload and suspended transport. Dynamic bed updating can be active optionally. Advection - diffusion of multiple water-borne constituents can also be considered within TUFLOW FV.

Example applications

TUFLOW 1D and 2D are widely used in the UK to assess flood risk in river floodplains and estuaries, including the potential impacts of dam breaks and storm surge overtopping / breaching. The 2D and 3D versions have been used in several coastal studies overseas but only in a relatively limited number of UK cases. TUFLOW FV has been used in the simulation of source tracking contamination within estuarine environments (McCarthy et al., 2017), while the classic version has been most often used for inundation studies. Examples includes, tidal re-inundation of restoration areas (Haines, 2013), inundation frequency of floodplains (Kaase & Kupfer, 2013) and coastal lagoon breaching (Wainwright & Baldock, 2015).

For more information visit: http://www.tuflow.com/Default.aspx

RMA Suite of Models

The RMA (Resource Modelling Associates) suite of models have been developed by Dr Ian King in Australia and extensively used by the U.S. Army Corps of Engineers. It has also by some UK-based consultants and academic researchers. The finite element models include packages to simulate stratified and unstratified flow, sediment transport, morphological response and water quality. They are designed for applications to estuaries, rivers and lakes.

The RMA models are based on a finite element approach, using a mesh of curved triangles and quadrilaterals. The variable mesh size enables irregular bathymetry and coastline to be accurately represented and a high-resolution mesh to be applied in areas of interest or rapidly changing flow. The model is capable of simulating tidal hydrodynamics in estuaries and bays, and the impact of structures, for example bridge crossings, on the flow dynamics. RMA-10 and RMA-11 are able to solve 1D, 2D and 3D problems within a single mesh, which considerably reduces computational time for large estuary or flood plain applications.

Hydrodynamics

RMA-2 is a 2DH flow model that solves the full nonlinear Shallow Water Equations together with the continuity equation. In RMA-2 (Norton et al., 1973) an eddy viscosity analogy is used to represent turbulence. Other forces considered are those due to bottom friction, wind stress and Coriolis effects. A fixed baroclinic influence may also be considered. Control structures such as weirs, tide gates or culverts can be incorporated as 1D or 2D elements. The wetting and drying of marshes, sandbanks, and overbank areas in tidal and flood flow can be simulated. Inclusion of stresses to represent wind or wave radiation stresses can also be input at the surface. RMA-10 (King, 1988) is an extension of RMA-2. It solves the shallow water equations in 3D including hydrostatic assumptions. This package is capable of simulating stratified flow dynamics with consideration for wetting and drying areas. Turbulence is included in a Reynolds stress form. In the vertical turbulence is represented by a quadratic parameterisation or a Mellor-Yamada Level 2 turbulence sub-model. Salinity and temperature are simulated using the advection-diffusion equation, which is coupled to density through an equation of state.

Sediment transport and Water Quality

RMA-10S is an extension of RMA-10 for morphological simulations. It can only be applied in 1D to estuary or river applications. It calculates the bed shear stress and net change in bed elevation resulting from net transport, erosion and deposition for sand or clay.

RMA-11 is the model used to simulate 1D, 2D or 3D sediment transport and water quality in estuaries, bays, lakes, rivers and coastal regions. It can use current vectors and elevation generated by RMA-2 or be coupled to RMA-10. The flow fields are used within the advection-diffusion constituent transport equations to simulate sediment transport. The addition of sediment sources and sinks can also be incorporated. Bed updating for cohesive sediment transport considers multi-layer thicknesses and consolidation. Pollutant loads may be incorporated as source input at discrete points, over elements, or as fixed boundary values. The water quality component simulates nutrient cycles with links to chlorophyll. RMA-11 was developed under contract to the Corps of Engineers and is used by many consultancies and research bodies worldwide. The code has been developed such that the element co-ordinate system is realigned with the local flow direction to enable the longitudinal and transverse diffusion terms to be separated. The model can be applied as a static state or dynamic model, using constant or interpolated flow information and has been used to simulate water quality in lakes, rivers, estuaries and groundwater systems. RMATRK is an alternative model to RMA-11, which can be used to simulate 2D particle tracking. Individual particles are tracked based on local velocities and a random component to emulate diffusion. Low dispersion systems can be modelled by calculating concentrations when simulating very large numbers of particles and counting the particle numbers within an grid element. Properties such as settling rates can be assigned to individual particles to model sediment transport or other transport processes.

The RMA flow models have been widely applied internationally to assess the impact of structures such as road and rail bridges on river and estuarine flows. Within the UK RMA flow models have been less widely used, although examples include Black & Veatch's (2006) use of RMA-10 to investigate tidal flows under different management scenarios in Suffolk estuaries, and Lawrence et al.'s (2004) use of RMA-2 to investigate flows within saltmarsh creek networks on the North Norfolk coast.

Areas of application include studies of water quality associated with riverine and estuarine discharges, algal growth and decay, dispersion of coliform bacteria, oil slick modelling, impacts on habitats, and cohesive and non-cohesive suspended sediment transport related to engineering schemes (King, 1992; Berger et al., 1993; MCL, 1995).

For more information visit: http://ikingrma.iinet.net.au/

DIVAST AND TRIVAST

DIVAST (Depth Integrated Velocities And Solute Transport) is a depth integrated, hydrodynamic and solute transport, time variant model, which was originally developed by Professor Roger Falconer at the University of Bradford for estuarine and coastal water quality applications. It has been further developed at Cardiff University (Lin et al., 2006) and can also be run as a quasi-3D model (TRIVAST) in which the water column is divided up into a number of integrated layers (Falconer et al., 1991). DIVAST is suitable for vertically well-mixed water bodies, dominated by horizontal, unsteady flow. The model simulates time-varying, water surface elevations, depth-averaged velocity, various water quality parameters and sediment transport, taking into account the hydraulic characteristics governed by the bed topography and the boundary conditions. The water quality constituents include salinity, total and faecal coliforms, biochemical oxygen demand (both ultimate and 5-day BOD), organic nitrogen, ammoniacal nitrogen, nitrate nitrogen, dissolved oxygen, algal biomass, and phosphorous. The model has been extensively calibrated and verified against laboratory and field data.

Hydrodynamics

DIVAST includes fluid momentum conservation and solute (i.e. pollutants and sediments) mass conservation, with particular emphasis on modelling dam break flows, and passing trans- and supercritical flows across 1D-2D boundaries. The hydrodynamics are solved using a finite difference approach. Solutions are based on the depth integrated Navier-Stokes equations and include the effects of local and advective accelerations, the Coriolis effect, barotropic and free surface pressure gradients, wind action, bed resistance and a simple mixing length turbulence model. The model simulates flooding and drying and assumes a second order parabolic velocity profile to distribute the wind stress.

Water Quality and Sediment transport

The advection-diffusion equation is solved for up to 12 water quality constituents and suspended sediment. The general depth integrated equations include local and advective effects, turbulent dispersion and diffusion, wind effects, source and sink terms, and decay and kinetic transformation processes. The equilibrium concentration for suspended flux is included through a choice of formulations.

Areas of application include flood risk assessment in river flood plains, assessment of dam and embankment breaching, water quality. The models have a wide range of applications. DIVAST has been used in an integrated modelling tool for river restoration studies to assess hydraulic and ecological conditions (Bockelmann et al., 2004) and extended to simulate sediment–bacteria interactions within surface waters (Gao et al., 2011). TRIVAST has also used to assess the impact of tidal stream turbines (Ahmadian et al., 2012; Brammer, 2014) and tidal barrages (Xia et al., 2010; Brammer, 2014), and adapted to examine sediment transport and bed level change (Kolahdoozan et al., 1998).

For more information visit:
http://www.designed4style.com/clients/websites/marcon/website/services/nm_divast.htm

NEMO

NEMO is a 3D ocean basin scale model for deep water and shelf applications being developed by a community of European scientists, including the UK Met Office and Natural Environment Research Council (NERC). The model is open source with limited distribution (user registration required) and has been developed to investigate ocean circulation, sea-ice, tracers and biochemistry, including forecasting capability. NEMO is developed on an Arakawa C-grid in a curvilinear coordinate system, with a choice of vertical coordinates (z or s, with the rescaled height coordinate formulation z*, or s*). The model domain typically used in the UK is the Atlantic Margin model at horizontal resolutions of 7 km, 1.5 km and 1/60th of a degree (~1.8 km) all with 51 vertical levels. Although still in development for coastal waters, the current model applies to a 10 m minimum depth; wetting and drying algorithms for intertidal areas are in development. As an example, the 1/60th of a degree model takes 32 days to simulate fully forced baroclinic dynamics for 1 calendar year using 2000 processors a High Performance Computer (HPC), while the 7 km model takes approximately 4 hours using 192 processors.

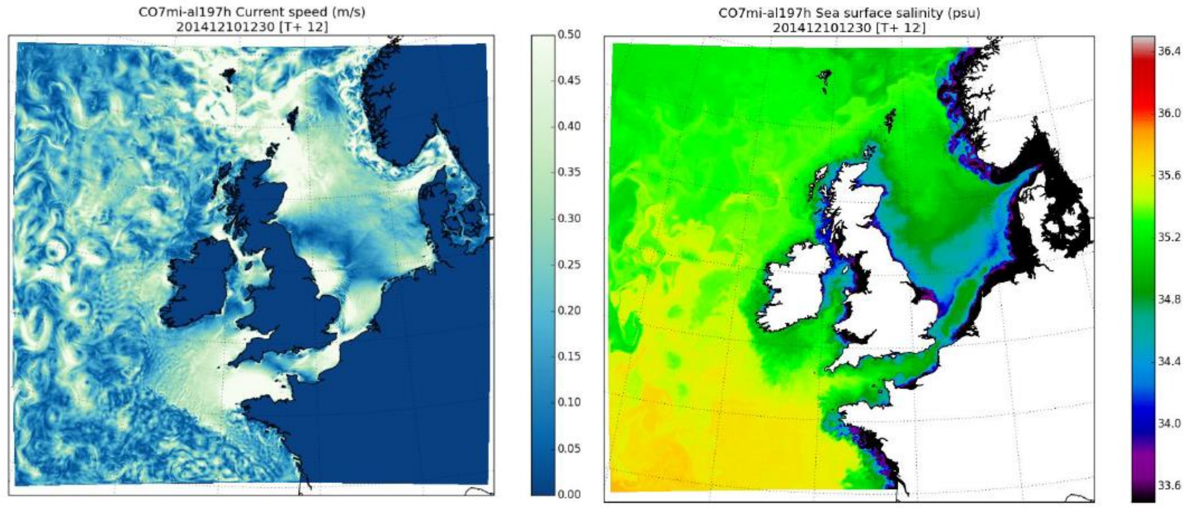


Figure A1.4. Surface currents (left) and surface salinity (right) from the UKO2 ocean configuration, which closely mirrors the 1.5 km model developed as part of the UK Environmental Predictions project

Example model outputs are shown in Figure A1.3 for the Met Office UKO2 ocean model, which is being developed towards future operational implementation as part of the EU Copernicus North West Shelf Marine Service. The model is designed to resolve smaller-scale processes that are known to play a key role in both shelf-break exchange and on-shelf circulation. Mesoscale eddies, for example, are crucial in transporting heat, freshwater and nutrients in the region.

The model simulates circulation due to tides and meteorological forcing (winds, pressure, atmospheric temperature, etc.). At present, it does not simulate sediment dynamics. A 2DH version is soon to be released as a more efficient setup for operational tide surge forecasting and there are plans to couple the model to Wavewatch III (Tolman, 1991) to incorporate wave-current interactions. Coupling options that are available include GOTM (Burchard, 2002) for turbulence closure and ERSEM (Butenschön et al., 2016) for ecosystem modelling.

Hydrodynamics

The model solves the Navier-Stokes equations along with a nonlinear equation of state, which couples the two active tracers (temperature and salinity) to the fluid velocity. The large-scale applications of this model make the gravitational force important, the orthogonal vector coordinates are thus linked to the Earth's surface. While ocean scale models are bounded by coastline on all sides, the AMM models have open boundaries that are nested within a global simulation. The boundaries of the model include air-sea and sea-ice interactions at the surface, river flux at the coast and the open boundary in a nested application is forced by tidal mean temperature and salinity fluxes and time-varying velocity and surface elevation. The air-sea interactions include momentum transfer and pressure continuity, in addition to heat and freshwater fluxes.

Areas of application include long term climate and ocean / shelf circulation studies (Ourmières et al., 2011; O'Dea et al., 2012; Holt et al., 2016; Buckingham et al., 2016). For the foreseeable future, the model is unlikely to use routinely in environmental impact assessments related to engineering of renewable energy schemes.

For more information visit: http://www.nemo-ocean.eu/

CORMIX

CORMIX (Cornell Mixing Zone Expert System) has been developed by MixZon Inc and is supported by U.S. Environmental Protection Agency. It is designed to simulate turbulent buoyant jet mixing behaviours for use in water quality assessments, and has been widely adopted as an industry standard method of assessment for such applications, in the UK and elsewhere.

The CORMIX software is designed for analysis, prediction and design of aqueous toxic or conventional pollutant discharges into diverse water bodies (Doneker & Jirka, 1991). The tool is aimed at assessing the geometry and dilution characteristics of an initial mixing zone so compliance with water quality regulations can be assessed. It can, however, also be used to predict the behaviour of a discharge plume over large distances.

The software uses a rule-based systems approach to data input and processing for the analysis of submerged single port discharges, multiport diffuser discharges (both of which can be non-buoyant and negatively buoyant) and buoyant surface discharges (which can be positively buoyant or non-buoyant). The use of efficient computational algorithms generates results in seconds for mixing zone problems with space scales of meters to kilometres and time scales of seconds to hours. These can be visualised as 3D outputs.

The types of effluents considered can be conservative, non-conservative, heated, brine discharges or contain suspended sediments discharging into flowing stratified or unstratified water bodies. The receiving water body can represent a stream, river, lake, reservoir, estuary or coastal waters. It is described by a plan shape, vertical cross-section and bathymetry. A density and velocity describes the system dynamics. The conditions can be taken as steady-state for simulating mixing over minutes to an hour, or where transient conditions are important the effective dilution of the discharge can be reduced relative to steady state conditions. Flow reversal in tidal conditions can also be included if required as can arbitrary ambient density current profiles. Discharge conditions are represented by the port diameter, source elevation above the bed, and orientation. The flux is represented by a discharge flow rate, momentum flux and buoyancy flux (relative density difference). The tool calculates near-field and far-field plume trajectory, shape, concentration, and dilution. Plume boundary interactions are considered and include dynamic near-field attachments. Density current behaviour with buoyant upstream wedge intrusion and stagnation points are predicted.

CORMIX can also be coupled to Delft3D-FV as a coupled modelling technique developed by MixZon Inc and Deltares. This is to address more complex coastal issues associated with industrial water discharge (e.g., Morelissen et al., 2016). This coupling enables simulations of non-steady flows and incorporates the effects of tides, winds, air pressure, density differences, waves, turbulence and wetting and drying. It can be applied to compute the far-field behaviour of the plume and recirculation effects. The coupling can be offline (one-way), running CORMIX to define the near-field source term for input into Delft3D for the far-field simulation, or online and dynamic (two-way), to account for time varying ambient conditions in the near-field. The coupling further includes the Distributed Entrainment Sinks Approach (DESA, Choi &Lee, 2007) to simulate mixing and transport in the intermediate field. Areas of application include power plant cooling waters (Schreiner et al., 2002), desalinization facilities (Palomar & Losada, 2010), drilling rig brine discharges (Doneker & Jirka, 2001) and wastewater outfalls in environments ranging from shallow rivers, reservoirs and lakes to estuaries and the deep oceans.

For more information visit: http://www.cormix.info/index.php

SWAN

SWAN (Simulating waves nearshore), is an open source 3rd generation spectral wave model developed at the Technical University of Delft for applications in coastal and inland waters (Booij et al., 1999). It simulates random, short-crested wind-generated surface gravity waves with swell waves contributions included though offshore boundary forcing.

The model uses either a structured (regular or curvilinear) or unstructured (triangular) mesh in a Cartesian or spherical coordinate system. Nested runs capture wave energy generated externally to the computational domain. Boundary forcing can be input from SWAN itself, WAVEWATCH III (Tolman, 1991) or WAM (Komen et al., 1994). The latter models are more appropriate for efficient simulations at ocean scales. The use of an unstructured grid offers an alternative to nesting, enabling optimal adaption of the mesh resolution in areas of complicated geometries, e.g. islands and irregular shorelines. This is particularly useful in coastal regions where the water depths can vary greatly over complex bathymetry. The code can be executed in serial or parallel. Simulations provide realistic estimates of wave parameters in coastal regions, lakes and estuaries for given wind, bottom and current conditions.

SWAN includes shoaling, refraction due to current and depth fields, frequency shifting due to currents and non-stationary depth. The model solves the wave action balance equation with source and sink terms. Other physical processes that are represented are wave generation by wind, three- and four-wave interactions, whitecapping, bottom friction and depth-induced breaking, dissipation due to aquatic vegetation, turbulent flow and viscous fluid mud, wave-induced set-up, transmission through and reflection (specular and diffuse) against obstacles, diffraction. Bragg-scattering and wave tunnelling are not simulated by SWAN and although wave forces are generated wave-induced currents are not simulated, this requires further coupling to a circulation model.

Outputs can be provided either in the form of maps, time series or tables. The model output include wave spectra in 1D or 2D, significant wave height and wave periods, average wave direction and directional spreading, spectral source terms in 1D or 2D, root-mean-square of the orbital near-bottom motion, wave dissipation, wave-induced force (based on the radiation-stress gradients), wave set-up, and diffraction parameter.

Areas of application include, real time wave forecasting for nearshore areas, annual hindcasts for coastal monitoring or other purposes (Amrutha et al., 2016), simulation of storm conditions (including hurricanes) and extreme value analysis for coastal flood risk assessment (Dietrich et al., 2011), modelling of long-term variability in wave characteristics (Akpınar et al., 2016), assessment of wave power potential (Robertson et al., 2016), assessments of the impact of wave energy farms on the coastal wave field (Rusu &Onea, 2016) and wave-current interaction at tidal energy sites (Guillou, 2017). The model is currently used by the Irish Marine Institute to produce 6 hour wave forecasts for the west coast of Ireland.
An example model application is shown in Figure A1.6 for Liverpool Bay. In this application SWAN has been run for a storm events 18-19th January 2007, including 1 day spin up time. Current and depth fields were provided by output from POLCOMS (Brown, 2010). The model was run serially over the ~ 180 m resolution grid, taking ~13 hours using a desk top PC.

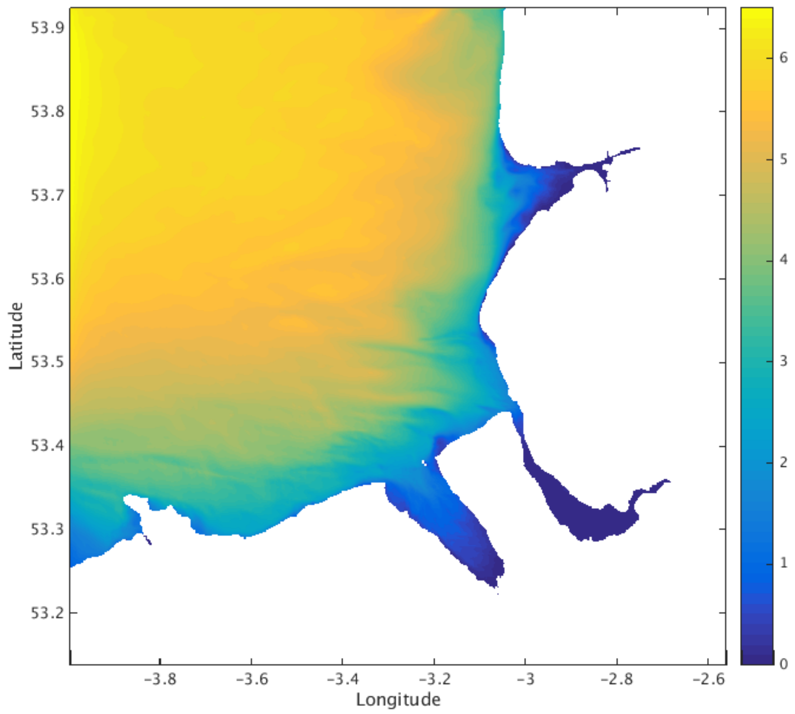


Figure A1.5. Maximum significant wave height simulated across Liverpool Bay for a storm 18th January 2007, generated using SWAN, courtesy of the Coastal Ocean Processes sub-group at the National Oceanography Centre

For more information visit: http://www.swan.tudelft.nl/

AMAZON

AMAZON-HBS (Hybrid Shallow Water/Boussinesq Solver) was developed at Manchester Metropolitan University to simulate seawall overtopping by waves. Waves are generated using the JONSWAP spectrum to closely resemble real ocean waves at the offshore boundary and a structure is represented at the coastal boundary. The model is used to calculate wave overtopping volumes for specified wave and still water levels and imposed structure design.

A combination of finite-volume and finite-difference methods are used to solve the Boussinesq equations, derived by integrating the Navier-Stokes equations in the vertical direction. The model is applicable to shallow water depths (depth/wavelength < 0.05), but also has additional dispersion terms to expend the application to intermediate depths (depth/wavelength < 0.5). The solution used to solve the nonlinear shallow water equations is both stable and robust. Pressure is assumed to be hydrostatic and the water motion is described by a depth-averaged velocity and total depth. A flexible mesh can be applied to define complex shaped grids that resolve the foreshore-structure profile providing high resolution where precise calculation is required.

Random waves are generated using the JONSWAP spectrum and simulated as bores. Across the bore mass is conserved, but energy is dissipated to represent a breaking wave. A seawall structure can be imposed where wave reflection and overtopping can take place. The water level can either represent the mean still water level of take a sinusoid to represent tidal variation. Sloping structures can be imposed with or without berms and with or without a crown wall. A curved wave return wall cannot be modelled. Vertical and near-vertical structures are represented as a steep slope. The flow at the crest is able to separate, overtop or return. Any water that flows up and over the top of the seawall is recorded as an overtopping volume. Bottom friction is incorporated to account for the structure and foreshore roughness, which causes wave dissipation. Comparisons between flume experiments and the computed values have shown that AMAZON-HBS accurately models wave propagation and overtopping. An additional development has been the introduction of a porous flow layer (e.g. as might be found in a dune or sand embankment). Porosity is taken as constant and the water exchange simulated using the Darcy (laminar) or Forchheimer (turbulent) equations (Reis et al., 2009).
Areas of application include harbour design and coastal defence vulnerability assessments AMAZON has been applied to assess proposed harbour breakwater schemes (Ries et al., 2009), in addition to scenario test cases. These cases include: a dam break, surge wave reflection, surge waves crossing a step, wave reflection at a vertical wall, wave runup and reflection at a sloping beach, wave overtopping at sloping seawalls, wave overtopping at vertical seawalls, wave overtopping at rock crown seawalls (Hu et al., 2000). Amazon has also been used to investigate wave overtopping of managed sand dune flood defences in southwest England (Royal Haskoning DHV, 2014).

For more information visit:
http://www.scmdt.mmu.ac.uk/cmmfa/projects/overtopping/amazonhbs.html

XBeach and X-Beach-G

XBeach is an open source 1DH and 2DH model for modelling the morphodynamic response of sandy shorelines to storm wave forcing. It was initially developed by

Roelvink (2003) but subsequently improved by UNESCO-IHE, Deltares and other partners (Roelvink et al., 2009). XBeach-G (McCall et al., 2014) is a version of the model applicable to gravel beaches. The model is a storm event model, which simulates wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, barriers (dunes or gravel) and backbarrier regions.

The 1DH XBeach model enables efficient computation of storm impact over a cross-shore profile, while the 2DH model allows assessment of storm impact over a sandy region. XBeach-G is currently limited to 1DH applications. The model applies a finite volume approach to a curvilinear or rectilinear grid for a local coastal area. The 1DH simulation for an event lasting a couple of tidal cycles typically completes within an hour on a PC, enabling multiple profiles or sensitivity analysis to be considered. For 2DH applications the model run times are much longer, typically of the order of a week to simulate an event (Dissanayake, 2014).

XBeach is designed to be a combined tool which simulates waves, circulation and beach response to storm impact at the event scale. It includes:

- long (infragravity) wave transformation (generation, propagation and dissipation).
- wave-induced setup and unsteady currents.
- bedload & suspended sediment transport
- dune face avalanching
- bed evolution & breaching.
- effects of vegetation & hard structures
- ship waves
- groundwater flow.

The model can be applied in non-hydrostatic mode, which is computationally demanding as it resolves short waves, or hydrostatic mode, which is more computationally efficient as short waves are averaged while the wave-group is resolved. The model solves the coupled 2DH equations for wave propagation, flow, sediment transport and morphology (depth-averaged). Flow is computed using the non-linear shallow water (Saint-Venant) equations with a non-hydrostatic pressure term. Wave forcing is added to the momentum equation from the wave action balance equation & a roller energy balance. Wave-current interaction incorporates depth & current refraction and radiation stresses. Wave dissipation is accounted for through breaking, bottom friction & the impact of vegetation, which schematized by a stem diameter & density. Groundwater flow is included and has been developed further for XBeach-G to include infiltration and exfiltration. For gravel beaches the exchange between groundwater and surface water is important for accurately simulating swash

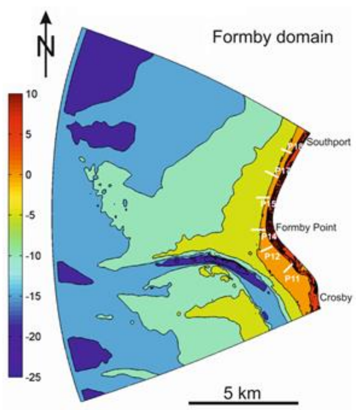
XBeach-G is similar to the SWASH model (Zijlema et al., 2011) and solves wave-by-wave flow and surface elevation variations due to short waves. For gravel beaches this is important due to steep slopes causing swash motion mainly at the incident wave and infragravity frequencies.

Suspended sediment is modelled using a depth-averaged advection-diffusion scheme with source-sink term. Wave breaking induced turbulence is accounted for through adjustment of the orbital velocity. The transport formulations distinguish between bedload and suspended load and can consider slope effects, wave skewness and wave asymmetry. The bed is subsequently updated based on gradients in the sediment transport rates. A morphological factor (MF) can be applied to speed up simulation times. In XBeach avalanching is included to simulate the slumping of sandy material from the dune face. A mix of sand fractions can be incorporated, characterized by the D_{50}, D_{15} and D_{90} sizes, if available, and bed layering is considered. Although spatially varying sediment distributions can be implemented within XBeach (Reniers et al., 2013), implementation is often limited by observations and a spatially uniform represented sand or gravel sediment size is usually applied. Within XBeach-G bedload and sheet load transport within the swash zone are considered for barrier evolution. At present XBeach / XBeach-G cannot simulate a mix of sand and gravel, distributed across the beach as a whole or as separate upper gravel and lower sand-dominated sections. Both applications allow for a non-erodible bed to be incorporated to represent the presence of a structure within a simulation, or to assess the impact of event scale evolution on flood hazards.

XBeach has been applied to flood and erosion risk management issues to help reduce uncertainty relating to the combination of wave and water level events that pose greatest flood hazard (Prime et al., 2016), the impact of storm clusters on shoreline and dune evolution (Dissanayake et al., 2015; Muller et al., 2017), and the impact of beach morphology and event driven evolution on wave overtopping hazards (Phillips et al., 2017). Due to the efficiency of the 1DH simulations it has also been used in early warning systems (Harley et al., 2015) and in the development of large databases behind decision support tools (Brown et al., 2017).

Dissanayake et al. (2015) used XBeach to assess the impact of storm sequences on the dune complex at Formby Point, Merseyside, and Phillips et al., (2017) used it to assess the effect of beach morphology in controlling seawall overtopping rates at Rhyl (with the consideration of scenario breach events).

An uncertainty assessment of gravel barrier overwash in relation to conditions that represent a 1 in 200 year wave-water level event was performed using Beach-G for the Dungeness foreshore (Prime et al., 2016). It was found that for a wind sea dominated location moderate water levels combined with moderate wave heights along the return period curve pose greatest flood hazard. In this application, XBeach-G was also used to provide discharge information into an inundation model to map the flood extent in response to the simulated waves and water levels.
Example applications for 2DH XBeach and 1DH XBeach-G application are illustrated in Figure A1.6. The 2DH domain extends approximately 12 km alongshore over a region of beach monitoring (shown as the white profile lines) and with the offshore boundary positioned at the depth of closure (~ 20 m). The simulation of two tidal cycles took approximately 8 days on a HPC (Dissanayake, 2014). The 1DH XBeach-G application (right figure) applied for a single storm tide (Prime et al., 2016) took an hour to run on a desktop PC.



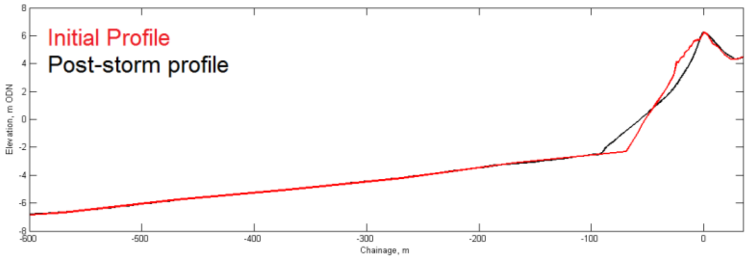


Figure A1.6. A 2DH model for the sandy Sefton coast setup as part of the EPSRC FLOODMemory project (Dissanayake et al., 2015) and a gravel barrier 1DH model from research at the University of Liverpool University for the Dungeness foreshore (above; Prime et al., 2016)

For more information visit: https://oss.deltares.nl/web/xbeach/home

CEM

The Coastal Evolution Model (CEM) is an open source one-line model for modelling shoreline evolution. It was initially developed at Duke University in North Carolina (Ashton et al., 2001; Ashton &Murray, 2006) but has subsequently been applied in the UK by the British Geological Survey and other researchers. The model is designed to simulate changing shoreline position over the long-term (centennial time scales) in response to the local wave climate.

Originally applied to predominately sandy, wave-dominated coastlines, it simulates shoreline response to time-scales ranging from years to millennia and on spatial scales ranging from km to hundreds of km. Initial studies assessing the evolution of sandy spits . Continued developments have extended its application to gravel shorelines (Brown et al., 2016), soft cliffs (Barkwith et al., 2014a) and enabled the inclusion of human interventions, such as beach nourishment or hard structures (Barkwith et al., 2014b).

The model is often discretised into 100 m^2 cells. For a long-term simulation it is calibrated against historic recession rates. A 10 year spin up time is recommended to allow the model to reach a stable state before running a long-term simulation (Barkwith et al., 2014a). For the example, a 100 year simulation of the Dungeness shoreline executed within 10 minutes for the 14 km stretch of coastline. The efficient run-times of the model enable it to be applied such that it can explore changes within the system, for example, changes in wave climate or impacts of alternative options for intervention.

The model uses a single wave climate representative of the coastal conditions the shoreline experience. At present the model does not incorporate the influence of tides or sea level rise. Volumetric alongshore sediment transport is calculated using the CERC equation for a uniform grain size. The shoreline evolution is then calculated as the result of gradients in the wave-driven alongshore sediment transport. The model follows the standard 'one-line' modelling approach, where the cross-shore dimension is collapsed into a single data point. The model domain is

therefore limited to relatively straight sections of coast, with features positions within longshore extent chosen. However, the model allows the plan-view shoreline to take on arbitrary local orientations, as complex shapes such as capes and spits form with in the domain. The geology underlying the sandy coastline and shoreface is represented in a simplified manner to allow the simulation of coastline evolution where sediment supply from an eroding shoreface may be constrained.
Areas of application include impact assessments of projected wave climates, assessments of future human intervention, erosion risk studies. To date the model has not been used to asses coastal schemes in the UK, although Barkwith et al., 2014a,b) have applied it to consider temporal and spatial variations in coastal erosion on the Holderness coast, and Brown et al. (2016) used it in exploratory modelling of a gravel mega-nourishment on the Dungeness foreland (Figures A1.7 and A1.8).
Figure A1.7 shows an example application to assess the possible use of 'sandscaping' on the Dungeness foreland, where the shoreline is able to evolve naturally between two sections where the policy is to hold the line (Brown et al., 2016).

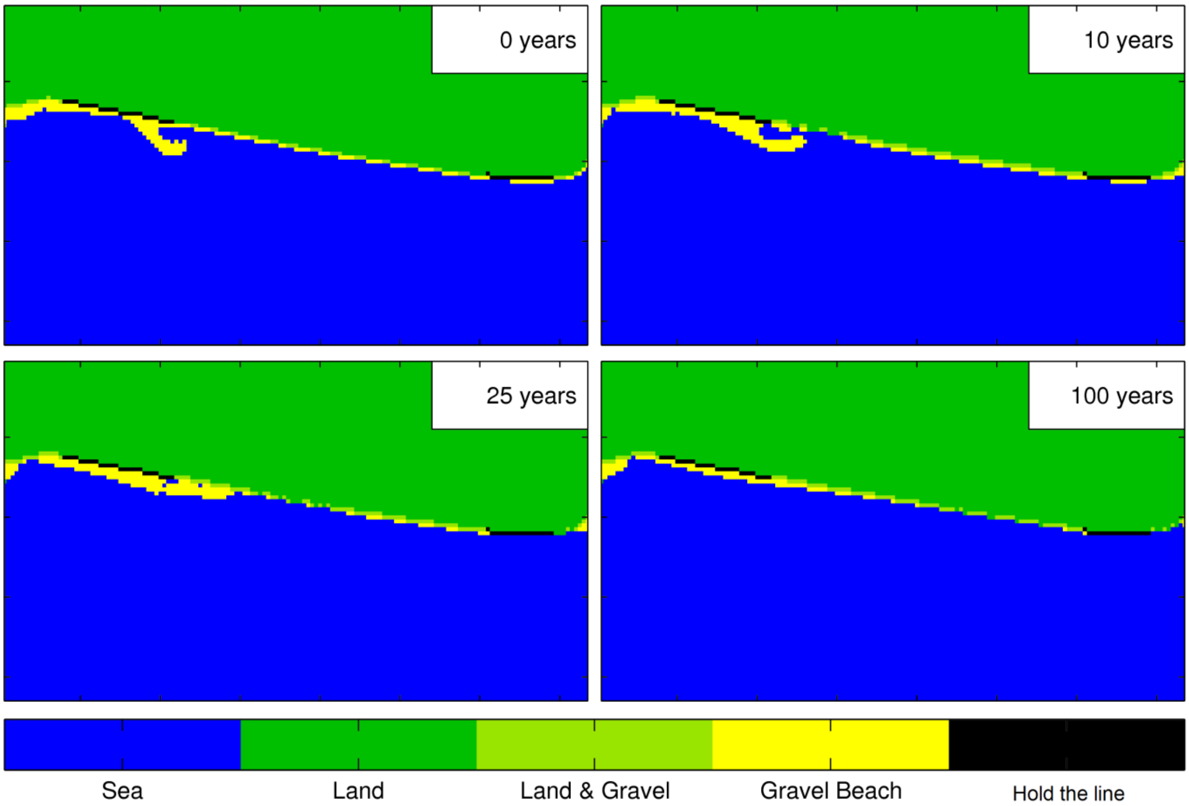


Figure A1.7. 'Sandscaping' on the Dungeness foreland

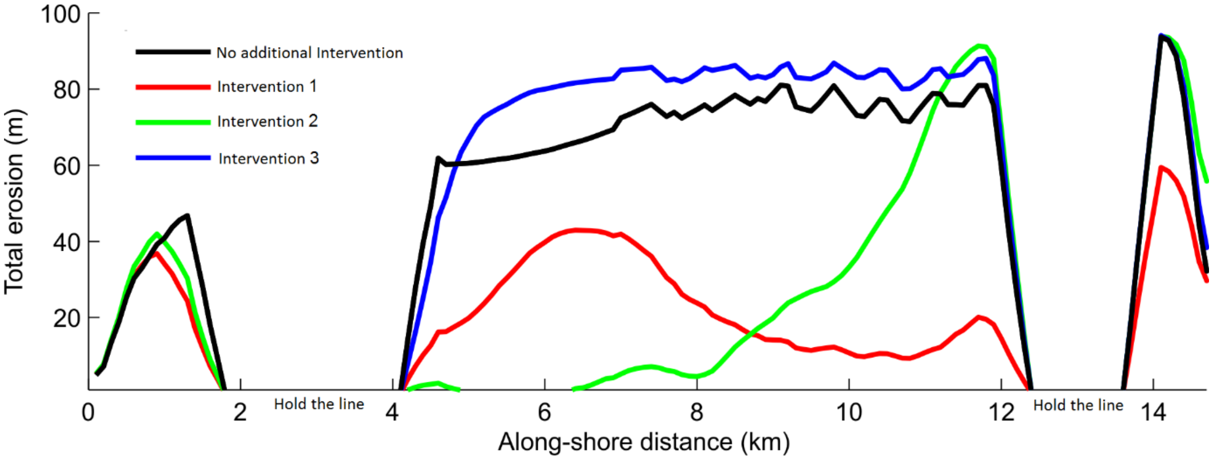


Figure A1.8. Coastal erosion over 100 year period along the Dungeness frontage for a range of mega-nourishment scenarios, simulated as part of the Sandscaping for Mitigating Coastal Erosion and Flood Risk project research at the University of Liverpool (Brown et al.., 2016)

For more information visit: https://csdms.colorado.edu/wiki/Model:CEM

APPENDIX B

EXAMPLES OF TYPICAL MODELLING REQUIREMENTS FOR DIFFERENT SCALE SCHEMES / INTERVENTIONS

Example 1 – Potential small to medium-scale impact – e.g. managed realignment within an estuary

Figure B1.1 illustrates a hypothetical case for a proposed small to medium-scale managed realignment to create intertidal habitat within an estuary.

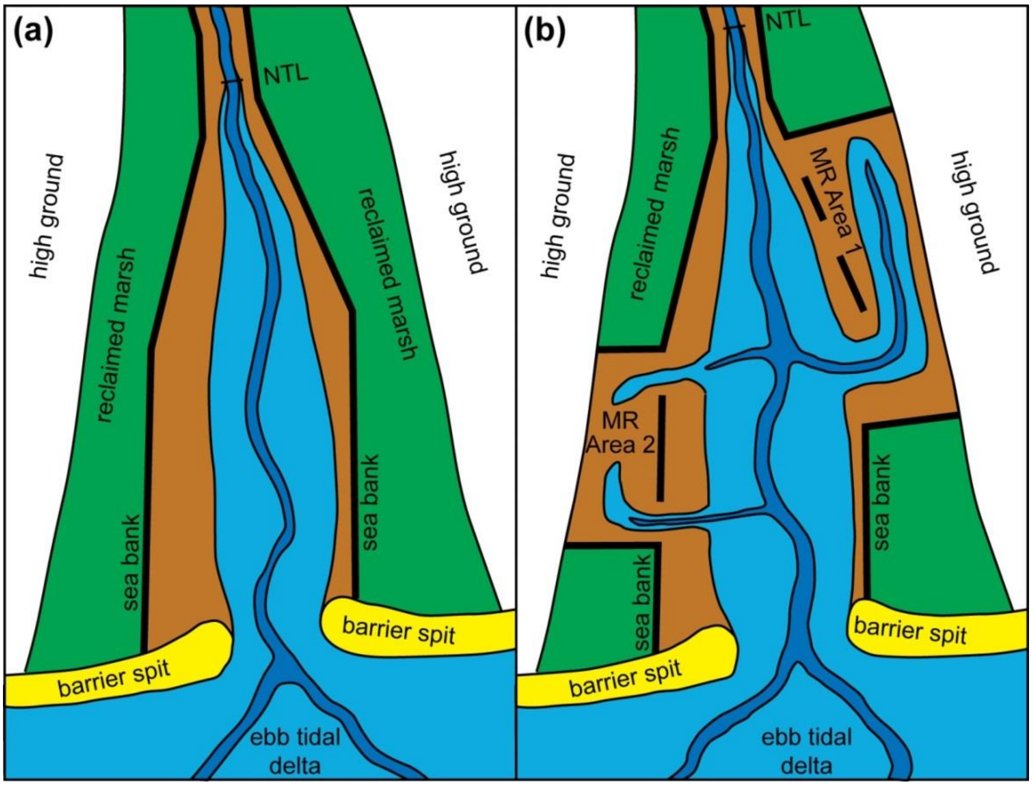


Figure B1.1 A Schematic representation of a proposed managed realignment scheme within a small to medium-sized estuary

Key questions to be answered in relation to this type of proposal are:

- Are the planned works themselves likely to cause any significant adverse effect on the estuary and its surroundings?
- how will the tidal regime within the estuary be changed, (a) immediately after scheme completion, and (b) in the medium to longer term?
- will the normal tidal limit (NTL) move landward, resulting in greater saline influence at the head of the estuary?
- will there be an increase or decrease in flood risk at the head of the estuary
- as the tidal prism will be increased following breaching / removal of parts of the sea banks, will flood and/or ebb current velocities change and if so by how much?

- will the increased tidal current speeds result in significant changes in bed shear stresses and changed patterns of intertidal and subtidal erosion and accretion within the estuary?

- Will the increased flow velocities be sufficient to cause a higher rate of low water channel movement / meandering, possible placing pressure of the remaining flood defences?

- What rate of sedimentation can be expected within the managed realignment area, and how will it change over time?

- What habitats can be expected to develop in the managed realignment areas, (a) shortly after scheme completion and (b) in the medium to longer term?

The scope and nature of the work necessary and possible order to address these questions should be determined during the Initial (Scoping) Assessment. This assessment should review the nature of data available relating to bathymetry / topography, local tidal levels, river flows, current speeds, suspended sediment concentrations, historical changes in the morphology of the estuary, including channel positions and normal tidal limit, sediment composition, suspended sediment concentrations, sediment budget of the estuary, habitat types present etc.

It is likely that the assessment would conclude that data analysis, numerical modelling and expert judgement methods should be used to address the issues identified. In order for numerical process-based modelling of hydrodynamics and sediment transport to be possible, the following would be required:

- bathymetric and topographic data of sufficient currency be available (either existing or to be obtained from new LiDAR and acoustic surveys)

- input process data (principally water levels) at the boundaries of a local area model of the estuary can be provided, either from a larger scale regional model or from observational data

- observed water level data for two or more points within the estuary can be obtained to calibrate and validate the model (this may require simultaneous deployment of at least two temporary tide gauges at different locations in the estuary for at least seven neap and seven spring tides)

- information about bed sediment characteristics (including particle size distribution, critical shear stress for mobilization and bed roughness)

- information about suspended sediment concentrations and particle size

The defined domain of the local area model should include the whole of the estuary, extend at least 2 km seaward of the estuary, and extend at least 1 km upstream of the normal tidal limit (potentially further in areas with very large tidal range, low gradient river valleys, and large meteorological surges).

In the case of estuaries where the freshwater input from the river(s) is small relative to the tidal prism, and where little or density stratification is to be expected, it would usually be adequate to use a 2D depth-average model (e.g. MIKE21 or TELEMAC 2D) to simulate water levels and mean current velocities, from which bed shear stresses can be estimated. If the estuary is sand dominated the sediment transport should be modelled using a Sand Transport (ST module); if the estuary is dominated by mud (cohesive sediments) a Mud Transport (MT) module should be used. In estuaries with mixed sediments both types of module should be used. The potential release and dispersion of sediment from point sources, such as the sites of artificial breaches created during the initial works, or points of localised channel downcutting following the works, should be modelled using a Particle Tracking (PT) module.

The modelling should be undertaken for a number of scenarios, including (a) the present (baseline) situation, (b) an immediate post-works situation with the estuary morphology largely unaltered but with parts of the sea banks removed, and (c) one or more future scenarios where the morphology of the estuary has evolved, including a “worst case” scenario where significant loss of intertidal sediment volume outside the remaining sea banks has occurred due to increased tidal flow velocities and sediment erosion / export from the estuary.

If the evolution of the artificial breaches is of particular concern (i.e. how they will widen / deepen over time), specific breach evolution modelling should also be undertaken.

The results of the modelling should be used to inform the final *Integrated Assessment,* alongside the results of Data-Driven Analysis. The latter should include:

- quantitative assessment of the tidal volumes and sediment volumes within the estuary by GIS analysis of DEMs prepared from LiDAR and bathymetric data (where available). Where several epochs of bathymetric / topographic data exist, this type of analysis should be repeated to provide information about changes in tidal volume and sediment volume over time. If three-dimensional data are not available but line survey data are (e.g. ground survey cross-section data), changes can be quantified in terms of volume per metre width at each cross–section

- a hypsometric model of the estuary should be created from the DEM and related to the known tidal levels and habitat distribution in the estuary in order to allow a predictive habitat development map to be created

- available information about sediment composition and any control points (natural rock outcrops or artificial structures) within the estuary should be reviewed in order to inform the assessment of likely long-term morphological evolution

- available information about suspended sediment concentrations, particle size, and composition should be reviewed and used in available simple empirical models to estimate medium to long-term rates of sediment accretion and bed level change, both within and outside the managed realignment areas.

Example 2: Potential medium-scale impact - e.g. Coastal New Nuclear Build

Figure B2.1 illustrates a hypothetical situation of a proposed New Nuclear Build (NNB) construction adjacent to an environmentally sensitive area.

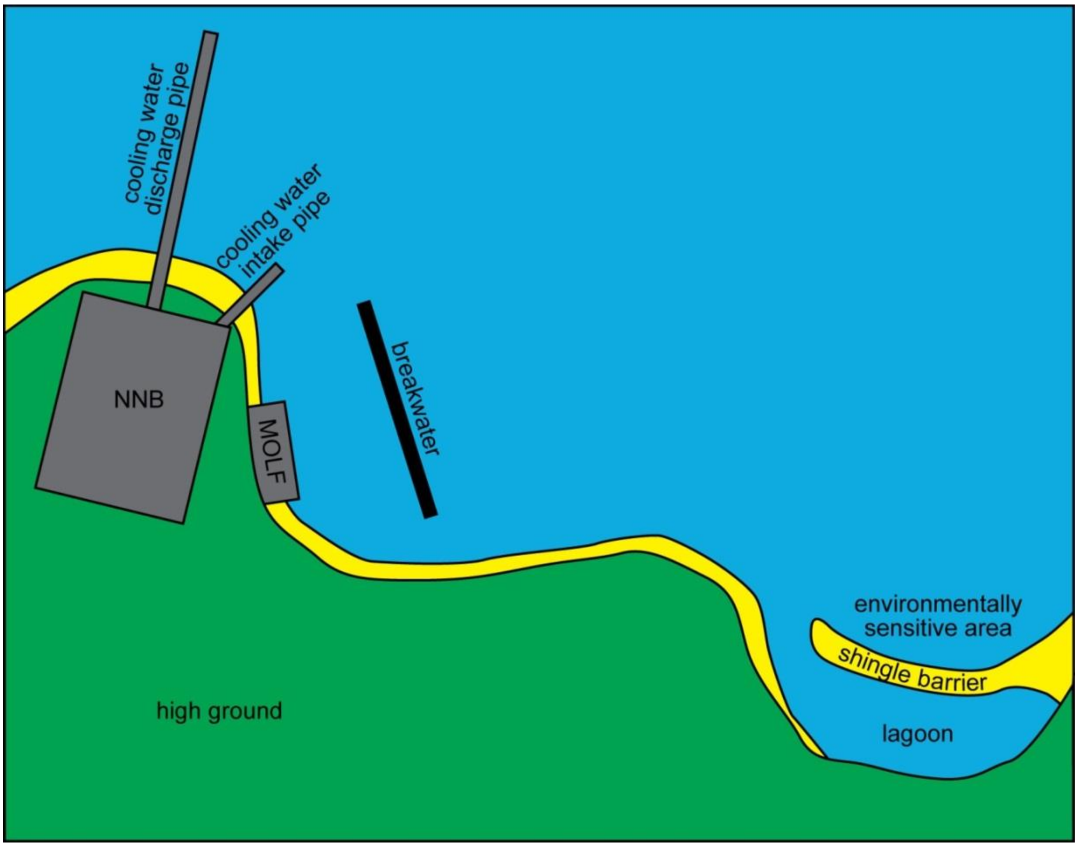


Figure B2.1. Schematic representation of a NNB, with associated infrastructure such as marine offshore landing facility (MOLF), offshore breakwater and cooling water intake and discharge pipes, adjacent to an environmentally sensitive area

Key questions relating to this type of development often include:

- will the construction of the offshore and onshore infrastructure have a significant impact on suspended sediment concentrations and water quality?
- when complete, will the offshore and shore-connected structures have a significant impact on the local wave climate, and potentially on the stability of the adjacent environmentally sensitive features?
- will the completed structures encourage medium to long-term scour of the adjacent sea bed, and/ or interfere with the alongshore transport of sediment?
- will the discharge of warm cooling water from the operational plant have a significant impact on alongshore sediment transport and / or aquatic ecology?

- will contamination from anti-fouling, anti-corrosion or radioactive materials pose a significant risk to water quality and marine life, either in the near-field area or the far-field?

As in any other case, the Initial (Scoping) Assessment should identify potential impact Sources, Pathways and Receptors, the adequacy of existing available data, requirements for further data collection, and the requirements for numerical modelling. In this type of situation it is highly likely that the Scoping Assessment would conclude that there is a requirement for numerical process-based modelling, probably using several different types of models and coupled models.

Given the range of potential impacts, varying in scale from local (near-field) to regional (far-field), best practice would involve the use of a number of modelling domains of differing scale and resolution. Regional scale (tidal) hydrodynamics and water quality can be investigated appropriately using a large spatial scale, relatively coarse mesh, model. Results from such a model can then be used to drive a smaller local area model, extending of the order of 20 km from the development site, which would have a higher resolution flexible mesh with a higher number of elements close to the development and potential receptors of particular interest. A third set of even higher spatial resolution model domains may also be required to examine in detail (using CFD modelling) the nature of flows and seabed interaction – e.g. in proximity to the cooling water intake and discharge pipes, the offshore breakwater or MOLF.

Whether or not 3D modelling, rather than 2D modelling, is required for the regional model domain will depend to a large extent on the nature of the marine environment involved, particularly if there is a significant region of freshwater influence associated with neighbouring estuaries. Where this is not the case, and where there is no significant thermal stratification or surface wind effects, 2D modelling may be adequate. In the case of the Local Area Model, however, 3D modelling is likely to be required to adequately incorporate the three-dimensional effects of currents and wave-current interaction around the offshore and shore-attached structures. Small-scale CFD modelling, by its very nature, has to be 3D.

Wave modelling will also be required to assess the potential impact of the structures on the local wave climate, and particularly on sensitive receptors such as the shingle ridge shown in Figure B2.1. A model such as SWAN or MIKE21 SW is commonly used for this purpose. Where there is a requirement to assess possible overtopping volumes at coastal structures, models such as MIKE21 BW and Europtop are widely used. The wave modelling should consider a number of different scenarios, including the most commonly experienced conditions and ‘extreme’ events where large waves combine with high water levels to create maximum potential impact at the shoreline. The potential effects of climate change and sea level rise should also be addressed by the modelling. Sensitivity tests should be carried out to assess the possible effect of changes in nearshore and beach morphology, and possible modifications to the design of the offshore / shore-attached structures.

Modelling of the Baseline and Post-Scheme sediment transport regimes will require the use of a Sand Transport and/ or Mud Transport module. The release and dispersion of sediment from individual points during construction of the breakwater, MOLF and cooling water pipes will also require the use of a Particle Tracking module. Potential water quality and ecology aspects can be addressed by appropriate modules in conjunction with the hydrodynamic model. Additional models such as CORMIX are also likely to be required to model the behaviour of potentially jetting discharges from the cooling water discharge pipe.

The data requirements for numerical modelling to be undertaken are broadly similar to those outlined with reference to Example 1 above, with the addition of inshore wave data to calibrate and validate the wave models. Where no suitable inshore wave data already exist, one or more wave buoys, AWAC or similar devices should be deployed at a relevant locations near the development and sensitive receptors. In the case of major infrastructure projects such as NNB, best practice would be to deploy and maintain at least one wave buoy and tidal level recorder during the construction and operational phases of the plant. Best practice would also include the deployment of one or more mini-Lander sensor arrays on the sea bed for several months, and to carry out a detailed seabed survey to determine spatial variations in bed type / composition / biota, in order to provide the best possible environmental baseline and background data sets for modelling, before construction begins.

The modelling results obtained should be evaluated alongside the results of other forms of Data-Driven Analysis, and possibly Physical Modelling, as part of the final Integrated Assessment. The Data-Driven Analysis should include studies of changes in coastal and submarine morphology and sediment distribution based on quantitative analysis of bathymetric charts, other bathymetric and topographic survey data, and sediment survey data. This analysis will allow an envelope of historical morphological (and possibly sediment) change to be identified, against which the results of future post-scheme completion monitoring can be compared.

Example 3. Potential large-scale impact – e.g. channel dredging and offshore dredge spoil disposal

Figure B3.1 illustrate a hypothetical situation of major capital dredging scheme to deepen part of the navigation approach and berthing area at a major port, together with placement of the arising dredge spoil at a disposal ground in the adjoining bay.

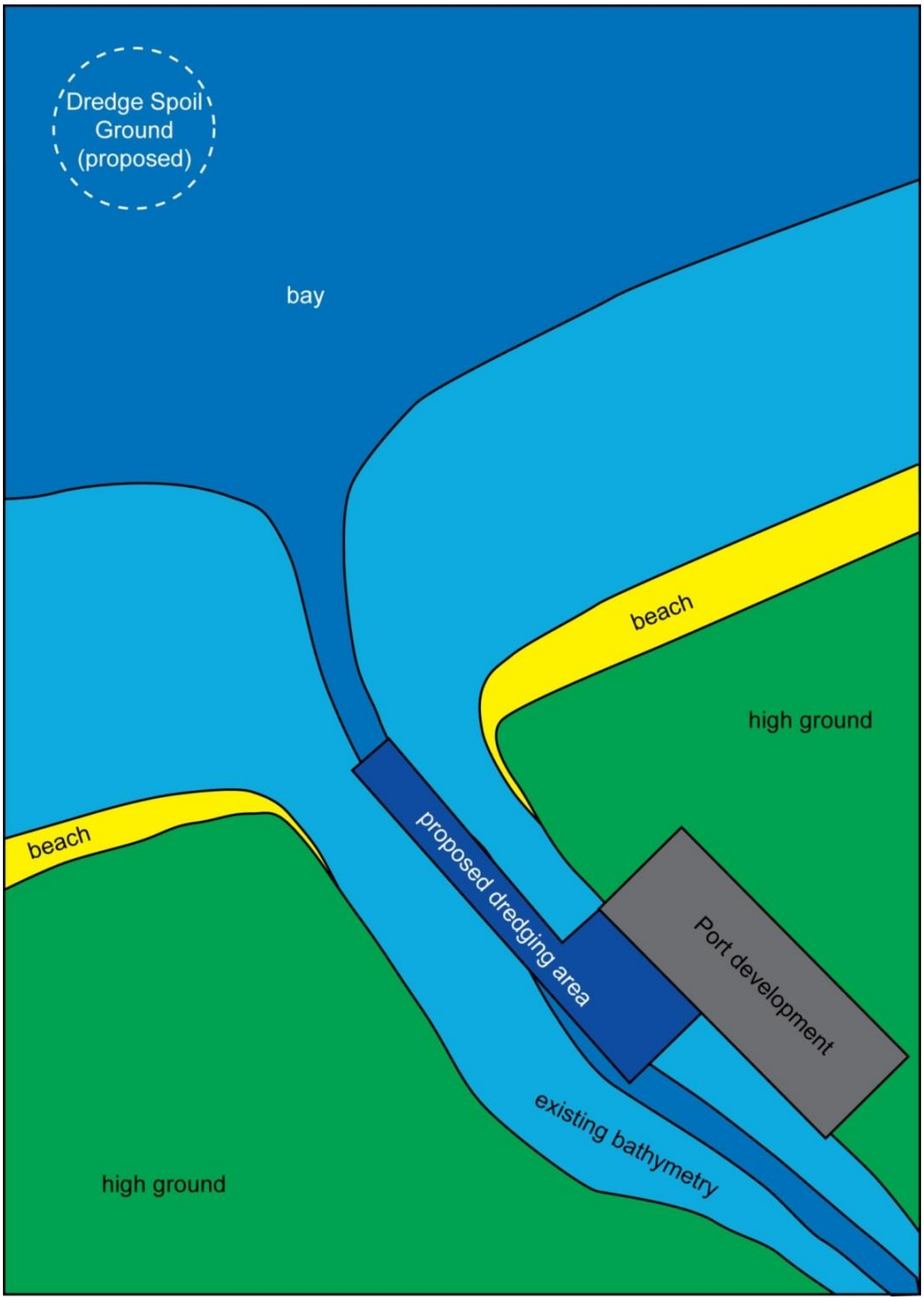


Figure B3.1 Schematic representation of capital dredging and dredge spoil disposal related to proposed port development

Key questions often associated with this type of development include:

- how will tidal levels within the estuary be affected?
- how will flood and ebb tidal current speeds be affected?
- how will bed shear stresses and sediment erosion / deposition potential be affected (a) within and adjacent to the dredging area) and (b) within and adjacent to the disposal area?
- how will the wave climate be affected and what will the effect be on adjacent shorelines?
- will dredge spoil disposal alter the sedimentary character of the sea bed at and around the disposal site?
- how far will fine sediment disturbed by the dredging and disposal operations travel, and what will be the effects on the wider bay?

The nature of Sources, potential Pathways and Receptors should be identified in the initial Scoping Assessment for the project. This will also normally identify a number of specific hypotheses which can be tested by the combined use of numerical process-based modelling and data-driven approaches.

The data requirements to allow numerical process-based modelling to be undertaken are broadly similar to those identified in relation to Examples 1 and 2 above, and include up-to-date bathymetry, adequate water level, wave and sediment data to allow model calibration and validation.

Since this hypothetical development lies near the mouth of a major estuary, discharge of freshwater into the adjoining bay is likely to be significant, and baroclinic effects will therefore need to be accommodated by the use of a fully 3D hydrodynamic model. Since there is a potential for regional-scale dispersion of fine sediment released by the dredging / disposal operations, the domain of the model should be sufficiently large to include the far-field and entire region of freshwater influence (ROFI), perhaps extending up to c. 100 km from the source. The 3D regional model may also need to be driven by a larger-scale continental shelf model, and sub-domains of the regional model used to examine local effects in more detail (e.g. around the dredged berths). Models such as MIKE3D and Delft 3D are widely used in environmental impact assessment for this type of application. However, where there is a requirement to represent the operative physical (and chemical / biochemical) processes in great detail, there may be advantages is using a research-based 3D modelling assemblage such as POLCOMS. A detailed example of the deployment of this model within the context of Liverpool Bay is provided below.

As in the case of Example 2, the results from 3D hydrodynamic and sediment transport modelling, wave modelling and combined current – wave modelling should be considered alongside the results from Data Driven Analysis as part of an overall

Integrated Assessment process. In this instance the Data Driven Analysis approaches should include information from analysis of historical charts, Sediment Trend Analysis based on a seabed sediment sampling campaign, examination of natural mineralogical and chemical signatures within the sediments, and results from short-term tracer / sea bed drifter studies.

Real-world example: Liverpool Bay

A modelling approach using POLCOMS (Holt & James, 2001) coupled to a shallow water version of WAM (Monbaliu et al., 2000; Bolanos et al., 2011) to simulate the dynamics within a coastal location is presented using Liverpool Bay as a case study example, with an additional focus on the Dee estuary for sediment transport modelling. Liverpool Bay is influenced by strong tidal flows and freshwater inflow from three estuary systems. Even in this energetic environment, with current speeds exceeding 1 m/s, baroclinic processes are found to be of great importance when considering residual circulation and sediment transport pathways (Brown et al., 2015).

Choice of model

When simulating a region of freshwater influence (ROFI) to assess long-term residual fluxes or the transport of suspended or dissolved particles the 3D baroclnic processes will be important. Even if the instantaneous current profile is dominated by the tide the long-term residuals can be influenced by the weak baroclinic circulations at slack water. In Liverpool Bay this residual circulation causes a net flux away from the Welsh coast in the surface layers and towards the Welsh coast near the bed (Palmer & Polton, 2011). The use of a 2D (depth-averaged) model can generate different residual flow patterns to that of different layers within the3D model. In locations where there is vertical variability in the residual circulation, care needs to be taken when representing the flow field for sediment dynamics. This is seen in Figure B3.2, where the surface and near bed residual flows are nearly opposing at some locations and the depth-average current falls part way between them. It is suggested that bedload and suspended sediment could take different pathways, both of which may differ to that of the depth-averaged circulation.

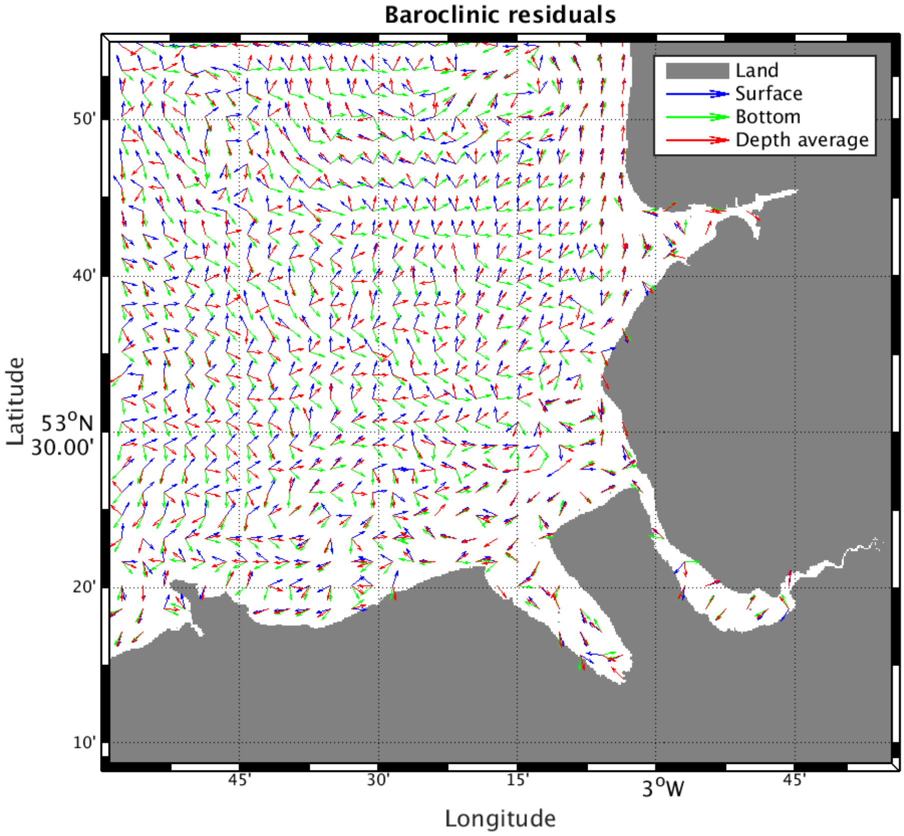


Figure B3.2: A baroclinic simulation of the residual currents in Liverpool Bay. Produced as part of the NERC iCOASST project, courtesy of the Coastal Ocean Processes sub-group at the National Oceanography Centre. The vectors are normalised by the current speed and show only the variation in current direction for the surface, bottom and depth-averaged velocities.

Variability in the baroclinic processes during an annual period will also have an influence on the longer term transport pathways. An example of the difference in modelled sand transport for a simulation with and without the inclusion of baroclinicity is shown in Figure B3.3 for Liverpool Bay. Without the influence of freshwater the transport is much more diffuse and reflects the tidal excursion. The impact is clearly greater on the finer sand due to the frequency of time spent at a higher position within the water column.

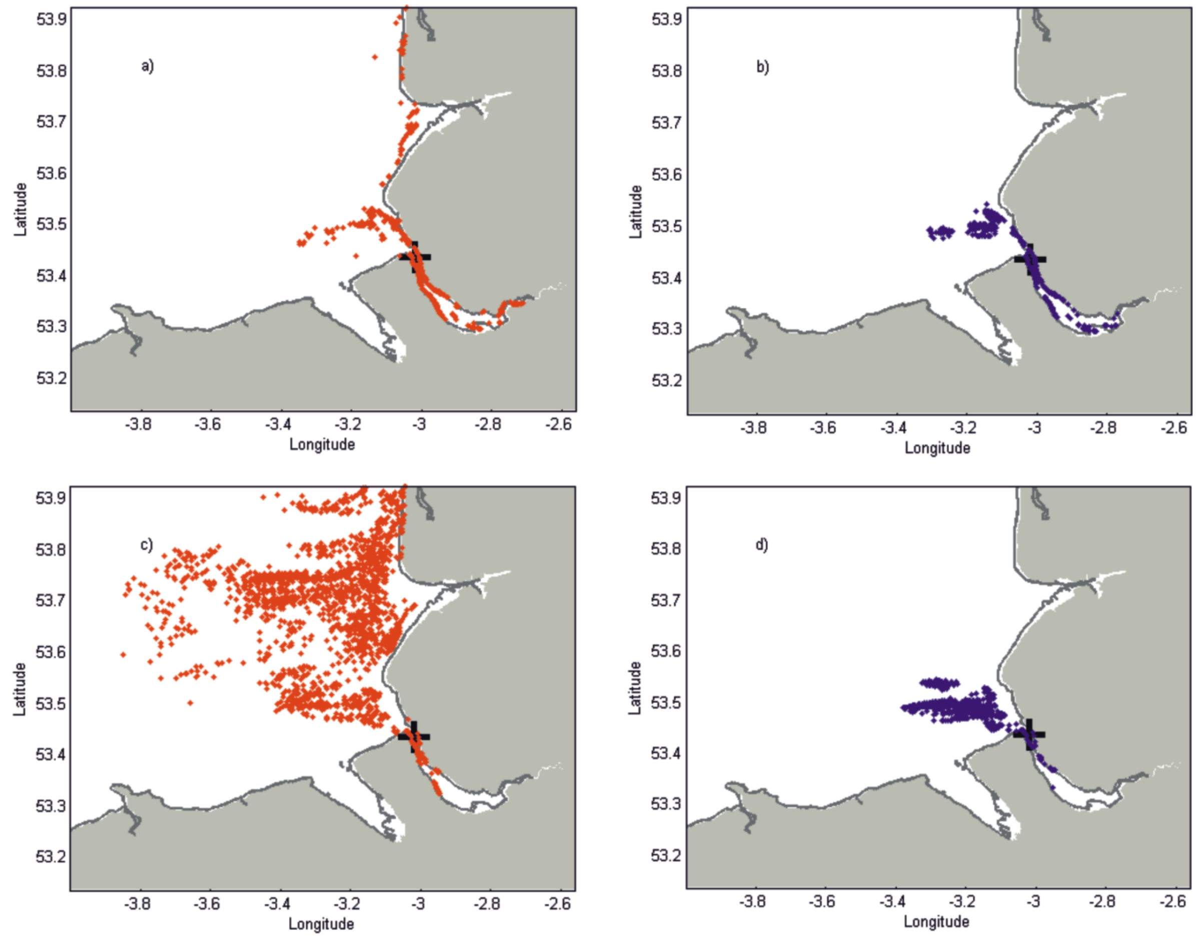


Figure B3.3 The position of the fine sand (Ws = 9 mm/s, left column) and medium sand (Ws = 35 mm/s, right column) released from the Mersey estuary mouth after a 3-month simulation with (top) and without (bottom) consideration of baroclinic processes.

The horizontal resolution applied within a modelling study should resolve the required ROFI processes and details of any complex channel-bank features within the domain for the purposes of the study. A grid resolution of the order of 200 m to 500 m is suggested for high resolution coastal studies (de Boer et al., 2006; Duran-Matute et al., 2014). In Liverpool Bay a 180 m model has been applied to be comparable to the local Rossby Radius (Brown et al., 2016). In shallow locations the vertical resolution requires careful selection to enable accurate positioning of the pycnocline, while in the shallowest regions the depth of the vertical layers needs to remain greater than the bottom roughness length to avoid instability in the bed shear stress calculations for sediment transport. In the model applied here 20 vertical levels are applied. Maximum water depths reach up to ~50 m and the bottom roughness length is 2.5 mm. In regions where there are large intertidal areas wetting and drying will influence the circulation, wave conditions and estuarine salinity intrusion (e.g., Yang and Wang, 2015). The use of a minimum depth can lead to differences in the simulated results to depths beyond that of the limiting depth value (Figure B3.4).

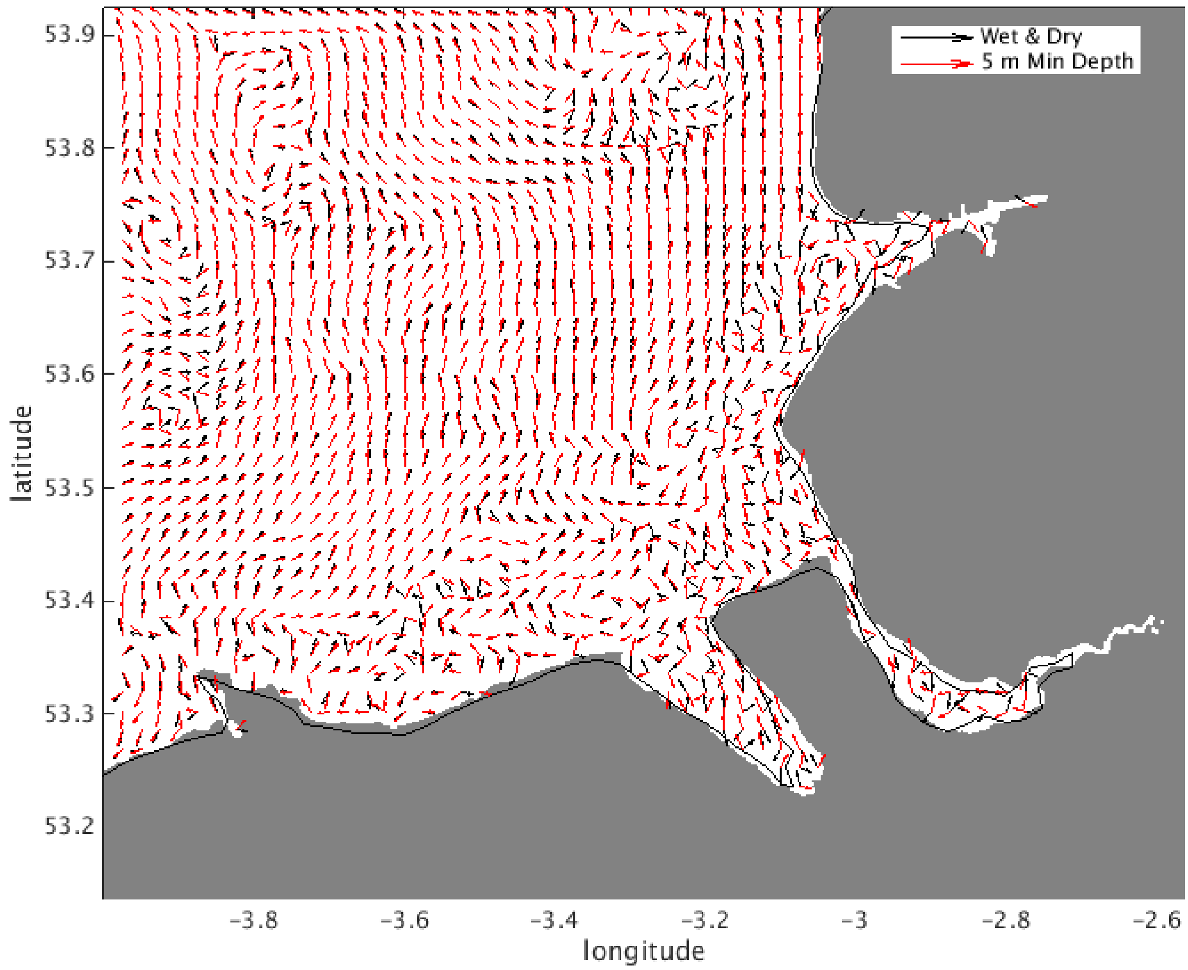


Figure B3.4: The residual current simulated for Liverpool Bay using POLCOMS with and without a 5 m minimum depth, courtesy of the Coastal Ocean Processes sub-group at the National Oceanography Centre.

If using a nested domain, the suggested ratio between the grid resolution is typically 3 to 5 (Warner et al., 2010) and the offshore boundary positioning will depend on the model's representation of the time-varying temperature and salinity flux. It cannot be assumed that the ROFI extent is equal to that of the littoral cell. Here the nesting applied is much courser to enable efficient simulations times for a multi domain system (12 km, 1.8 km to 180 m). Validation using observations available from the Liverpool Bay coastal Observatory (Howarth & Palmer, 2011) have been used to validate this set up. For a model that imposes a tidal-mean flux the offshore extent of the boundary should ideally be positioned beyond the maximum possible extent of the ROFI with allowance for the tidal excursion (Brown et al., 2016). Here, thermal satellite imagery, cruise data and operational modelling systems were available to provide information to identify the required extent of the model domain. The positioning of the boundary will not only depend on the representation of the offshore fluxes by the model, but also what data is available to force the boundary.

When using a coupled wave-circulation model it is important to identify if the area is fetch limited with regards to waves and surge generation. Depending on the size of the domain and the limitations or openness of the coast, external boundary forcing may be required. For Liverpool Bay different fetches have been found to be important for extreme wave and surge generation. The largest surges are associated with fetches from the boundary of the eastern Irish Sea towards the SW, while extreme waves are locally generated across fetches toward the west (Brown et al., 2010). In the POLCOMS-WAM model applied in this study two-way coupling between waves and currents have been considered. Wave refraction and breaking is influenced by the time-varying currents and elevations, enhanced stress at the bed and surface in addition to radiation stresses generating wave-driven circulation are considered to capture the event scale dynamics. However, due to the computational cost of the wave simulations, annual timescales have only considered the circulation.

Sediment dynamics have been incorporated within the Dee estuary, where observations of sediment concentrations are available in the two main channels close to the estuary mouth. The transport of cohesive particles has been considered, using a relationship between settling velocity and the turbulent shear stress derived from observations to represent the flocculation processes (Ramirez Mendoza et al., 2014). Signals in the sediment transport rates of flocculated particles vary depending on whether the conditions are current-dominated, wave-current, or wave dominated (Ramirez Mendoza et al., 2016). Under calm conditions sensitivity analysis of the model setup has found suspended transport results primarily from the advection of the longitudinal concentration gradient in combination with resuspension and vertical exchange processes rather than from input from the river source (Amoudry et al., 2014). This demonstrates how spatial information of the bed sediment characteristics could lead to improved simulations of sediment transport.

Model forcing

POLCOMS-WAM is forced at the offshore boundary by temperature, salinity, elevation, velocity and spectral wave fields. The hydrodynamic and metrological boundary forcing come from a pre-operational modelling system run as part of the Liverpool Bay Coastal Observatory. A tidal-mean depth-varying temperature, salinity and velocity boundary condition is provided to calculate the external fluxes, while elevations and depth-averaged velocity components are prescribed at 30-minute intervals to capture the tidal variability in these fields. Spectral wave boundary conditions are generated over the northeast Atlantic and downscaled through the Irish Sea to force the Liverpool Bay model at an hourly frequency. Wave-current coupling is considered within the middle (the 1.8 km Irish Sea model) and highest (Liverpool Bay) resolution nests. River inflow at the coast was provided at locations where a daily-mean discharges were available with a catchment factor to correct for the up-river position of the gauge.

The meteorological conditions acting on the free surface include wind components at 10 m height, atmospheric pressure, air temperature, specific humidity, cloud cover and sensible heat flux. Winds and atmospheric pressure are provided at hourly intervals to represent storm events, while the other parameters are considered at 3 hourly intervals.

At the local Liverpool Bay scale offshore boundary conditions are found to influence the local dynamics. The horizontal density gradient is strongly controlled by the salinity conditions at the external boundary rather than the river inflow at the coast (Brown et al., 2016). Surge elevations within the bay have a low sensitivity to wave-current coupling options within the local model (Brown et al., 2011), while at the Irish Sea scale there is a higher sensitivity to wave enhanced surface roughness (Brown & Wolf, 2009).

Validation

When considering validation of different processes it is important to have a clear understanding of how the dynamics of a system may vary to inform the positioning of instruments or to identify what processes can be validated from the available observations. Taking the Dee estuary as an example, there are very different dynamics between the two main channels (Brown et al., 2014). The Hilbre channel displays a vertically shear exchange flow, while the Welsh channels displays a horizontally sheared exchange flow. In this case, positioning of an instrumented rig in the Welsh channel may collect only part of the regime within this channel. Extensive model validation has been possible in Liverpool Bay due to the existence of the Liverpool Bay Coastal Observatory between 2002 and 2012 (Howarth and Palmer, 2011). The observatory provides information at set locations of depth-varying current, temperature and salinity information from CDT and ADCP data, both in the coastal ROFI and within the Dee estuary. An offshore wave rider part of the CEFAS wavenet programme complimented the short deployments of a triaxys wave buoy within the Hilbre channel. CTD data collected during cruises provides information about the spatial variability in the ROFI dynamics, but cannot provide an instantaneous snap shot of the density gradients. Together this information enables validation of the waves (height, period, direction) and depth-varying current, temperature and salinity fields. The importance of having multiple points of information is show when calibrating the wave conditions entering the Dee estuary (Brown, 2010).

For sediment dynamics a LISST was used to obtain volumetric concentrations of 32 grain sizes in suspension in the Dee estuary. A fast sampling ADV (16 HZ at 20 minute intervals) also allows the calculation of turbulent stresses to calibrate a relation to represent the flocculation processes. SPM samples were also obtained from water samples collected during hourly CTD casts. The mass concentrations are used to define a relationship to convert the LISST data to mass concentrations (Ramirez Mendoza et al., 2014).

Uncertainty

For inputs or parameter setting that are considered important for a given study, but have unknown value a sensitivity analysis is performed to assess the uncertainty in the simulation created by the default or no value settings. Such an analysis was performed on the river inflow temperature and salinity values imposed in both the Irish Sea and Liverpool Bay models to assess the uncertainty associated with these unknown values. Consideration of temperature was assessed as seasonality can influence the buoyancy of the freshwater plume (Hopkins and Polton, 2012). The parameter settings within GOTM were also varied to assess the impact of the turbulence closure scheme on the transport of freshwater into Liverpool Bay. In all cases, the freshwater plume was found to be more sensitive to the external conditions

Model application

Once satisfied with the accuracy of the model capability at simulating the undisturbed conditions the model can be used to assess the potential impact of offshore structures, such as energy generation devices, dredging and spoil disposal. The 180 m POLCOMS model for Liverpool Bay has been to assess the impact of medium-size windfarm developments within the Bay (Eddon, 2017). The choices made to represent the presence of the windfarm has been found to have an important impact on the simulated changes. To incorporate the impact of a windfarm the structures have been represented as a momentum sink and a source of turbulent kinetic energy. Impact assessment reveals it is important to account for both terms when considering the dynamic response of the ROFI. The spatial representation of the windfarm also needs consideration relative to the grid resolution. For a 180 m model resolution representing the windfarm as an area-averaged source-sink term over the area of the windfarm is found to be more appropriate than representing the individual pylons at appropriate grid nodes. This is due to the model grid in this case being unable to fully resolve the flow between the pylons.

APPENDIX C

SUMMARY OF MODEL MODULES, MAJOR INPUT PARAMETERS AND COEFFICIENTS REQUIRED FOR THE DHI MODELLING SUITE

1. **MIKE Zero** (MIKE framework tools required to run the other modelling systems)
    1.1. Time series
    1.2. Profile Series
    1.3. Data Manager
    1.4. Grid Series
    1.5. Plot composer
    1.6. Result Viewer
    1.7. Bathymetries
    1.8. Climate Change
    1.9. Ecolab
    1.10. Auto Calibration
    1.11. EVA Editor
    1.12. Mesh Generator
    1.13. Data Extraction FM
    1.14. MIKE Zero Toolbox
    1.15. WS Wave Analysis Toolkit
        1.15.1. WS Linear Spectral Analysis
        1.15.2. WS Digital Filtering Analysis
        1.15.3. WS Directional Wave Analysis
        1.15.4. WS Crossing Analysis
        1.15.5. WS Reflection Analysis
        1.15.6. WS AWACS Reflection Analysis
        1.15.7. WS Trend Removal
2. **MIKE HYDRO** (modelling system for catchments, rivers and floodplains)
    2.1. MIKE Hydro Model
3. **MIKE 11** (1-D modelling system for rivers and channels)
    3.1. Simulation
    3.2. River Network
    3.3. Cross Sections
    3.4. Boundary Condition
    3.5. RR Parameters
    3.6. HD Parameters
    3.7. AD Parameters
    3.8. ST Parameters
    3.9. FF Parameters
    3.10. Correlation Analysis & Gap Filling
    3.11. Batch Simulation
    3.12. River Channel Design
    3.13. MIKE 11 Eco Lab
    3.14. Data Assimilation
4. **MIKE 21** (2-D modelling system for estuaries, coastal waters and open seas)
    4.1. Flow Model
    4.2. Flow Model FM
    4.3. Spectral Waves FM
    4.4. Boussinesq Waves
    4.5. Elliptic Mid Slope Waves
    4.6. Parabolic Mild Slope Waves
    4.7. Non-Cohesive Sediment Transport
    4.8. Curvilinear Flow Model
    4.9. MIKE 21 Toolbox
5. **MIKE 3** (3-D modelling system for estuaries, coastal waters and open seas)
    5.1. Flow Model
    5.2. Flow Model FM
    5.3. MIKE 3 Toolbox
6. **MIKE 21/3** (Integrated Models (integrated and coupled 2-D and 3-D models)
    6.1. Coupled Model FM
    6.2. MIKE21/3 Oil Spill
    6.3. MIKE 21/3 Particle Tracking
7. **LITPACK** (modelling system for littoral process and coastal kinetics)

    7.1. LITPACK
    7.2. LITPACK Toolbox
    7.3. Littoral Processes
8. **MIKE FLOOD** (flood modelling system for river, floodplains and urban areas)
    8.1. MIKE FLOOD
    8.2. MIKE FLOOD Toolbox
9. **MIKE SHE** (modelling system for integrated groundwater and surface water)
    9.1. Flow Model
    9.2. Well Editor
    9.3. UZ Soil Properties
    9.4. ET Vegetation Properties
    9.5. Water Balance Calculation
    9.6. Simple Shape Editor
    9.7. MIKE SHE Toolbox

MIKE 21 Flow Model FM

MIKE 21 Flow Model FM is a modelling system with data calculated from and output onto a flexible mesh. The modelling has been developed for applications within oceanographic, coastal and estuarine environments. The basic computational component of the model is performed by a Hydrodynamic Module, but additional modules (Transport, ECO Lab / Oil Spill, Mud Transport, Sand Transport and Particle Tracking) can also be implemented.

The modelling system is based on the numerical solution of the two-dimensional shallow water equations - the depth-integrated incompressible Reynolds averaged Navier-Stokes equations. Thus, the model consists of continuity, momentum, temperature, salinity and density equations. In the horizontal domain both Cartesian and spherical coordinates can be used. The spatial discretization of the primitive equations is performed using a cell-centered finite volume method. The spatial domain is discretized by subdivision of the continuum into non-overlapping element/cells. In the horizontal plane an unstructured grid is used comprising of triangles or quadrilateral element. An approximate Riemann solver is used for computation of the convective fluxes, which makes it possible to handle discontinuous solutions.

An example run listing for MIKE 21 Hydrodynamic Flow Model

The following flow list details the required steps to prepare a MIKE 21 Flow Model, and lists the input parameters required at each stage:

1. Domain
    1.1. Load the bathymetry mesh previously created in MIKE ZERO (1.12 above).
    1.2. Specify the map projection type (e.g. OSGB36, UTM, lat and long)
    1.3. Specify a minimum depth cutoff (default = highest elevation in the dataset)
    1.4. Specify a datum shift (default = 0 m)
    1.5. Provide a recognizable name to each open boundary in the bathymetry dataset
2. Time
    2.1. Specify the number of time steps to compute (default = 100)
    2.2. Specify the time step interval (default = 30 seconds)
    2.3. Specify a simulation start date and time (default = 01/01/2004 00:00:00)
    2.4. Specify a simulation end date and time (default = 01/01/2004 00:50:00)
3. Hydrodynamic Module inputs

3.1. Solution Technique
  3.1.1. Shallow water equations
    3.1.1.1. Specify the time integration: higher order (default) or low order, fast algorthim
    3.1.1.2. Specify the Space discretization: higher order (default) or low order, fast algorithm
    3.1.1.3. Specify the minimum time step (default = 0.01 seconds)
    3.1.1.4. Specify the maximum time (default = 30 seconds)
    3.1.1.5. Specify the critical CFL number (default = 0.8)
  3.1.2. Transport equations
    3.1.2.1. Specify the minimum time step (default = 0.01 seconds)
    3.1.2.2. Specify the maximum time (default = 30 seconds)
    3.1.2.3. Specify the critical CFL number (default = 0.8)
3.2. Depth
  3.2.1. Specify depth correction type: none (default) or specify bed level change:-
    3.2.1.1. Specify either: (a) varying in space, constant in time, or (b) varying in time and domain. For either, a datafile should be loaded which describes how the depth varying in space and/or time
3.3. Flood and Dry
  3.3.1. Specify either: (a) No flood and dry, (b) Standard flood and dry (default), or (c) Advanced flood and dry including floodplain. If flood and dry is specified:-
    3.3.1.1. Specify drying depth (default = 0.005 m)
    3.3.1.2. Specify flooding depth (default = 0.05 m)
    3.3.1.3. Specify wetting depth (default = 0.1 m)
3.4. Density
  3.4.1. Specify either: (a) Barotropic (default), (b) Function of temperature and salinity, (c) Function of temperature, or (d) Function of salinity. For b-d:-
    3.4.1.1. Specify reference temperature (default = 10 °C)
    3.4.1.2. Specify reference salinity (default = 32 PSU)
3.5. Eddy Viscosity
  3.5.1. Specify the eddy type: (a) No eddy, (b) Constant eddy fomulation, or (c) Smagorinsky formulation (default). If b or c are specified:-
    3.5.1.1. Constant eddy formulation – specify either: (a) constant value (default = 0.002 m^2/s), (b) varying in domain, or (c) varying in time and domain. For b or c a datafile should be loaded which describes how the eddy varies in space and/or time.
    3.5.1.2. Smagorinsky formulation – specify either: (a) constant value (default = 0.28), (b) varying in domain, or (c) varying in time and domain. For b or C a datafile should be loaded which describes how the eddy varies in space and/or time.
      3.5.1.2.1. Specify minimum eddy viscosity (default = 1.8×10^{-6} m^2/s)
      3.5.1.2.2. Specify minimum eddy viscosity (default = 1.0×10^{10} m^2/s)
3.6. Bed Resistance
  3.6.1. Specify the resistance type: (a) No bed resistance, (b) Chezy number, or (c) Manning number (default). If b or c are specified:-
    3.6.1.1. Chezy number – specify either: (a) constant value (default = 32 $m^{1/2}/s$), (b) varying in domain, or (c) varying in time and domain. For b or c a datafile should be loaded which describes how the eddy varies in space and/or time.
    3.6.1.2. Manning number – specify either: (a) constant value (default = 32 $m^{1/3}/s$), (b) varying in domain, or (c) varying in time and domain. For b or c a datafile should be loaded which describes how the eddy varies in space and/or time.
3.7. Coriolis Forcing
  3.7.1. Specify the Coriolis type: (a) No Coriolis force, (b) constant in domain, or (c) varying in domain (default). If b or c are specified:-
    3.7.1.1. Constant in domain - specify the reference latitude (default = 0 degrees)
    3.7.1.2. Varying in domain – no input parameters required
3.8. Wind Forcing
  3.8.1. Specify either: (a) Exclude wind forcing (default), or (b) include wind forcing. If wind forcing is included, specify either (a) constant, (b) Varying in time, constant in domain, or (c) varying in time and domain:-
    3.8.1.1. Constant wind forcing
      3.8.1.1.1. Specify wind speed (default = 0 m/s)

3.8.1.1.2. Specify wind direction (default = 0 degrees)
3.8.1.1.3. Specify soft start interval (default = 0 seconds)
3.8.1.2. Varying in time, constant in domain
3.8.1.2.1. Load a datafile which describes how the wind varies in time
3.8.1.2.2. Specify soft start interval (default = 0 seconds)
3.8.1.3. Varying in time and domain
3.8.1.3.1. Load a datafile which describes how the wind varies in space and time
3.8.1.3.2. Specify a neutral pressure (default = 1013 hPa)
3.8.1.3.3. Specify soft start interval (default = 0 seconds)

3.9. Ice Coverage

3.9.1. Specify either: (a) No ice coverage (default), (b) specified ice concentration, (c) specified ice thickness, or (d) specified ice concentration and thickness:-
3.9.1.1. Specified ice concentration
3.9.1.1.1. Load a datafile which describes how the ice varies in time and domain
3.9.1.1.2. Specify a critical concentration (default = 0.9)
3.9.1.1.3. Specify whether to include or exclude ice roughness height data, and if so with a constant value (in metres), varying in domain, or varying in time and domain.
3.9.1.2. Specified ice thickness
3.9.1.2.1. Load a datafile which describes how the ice varies in time and domain
3.9.1.2.2. Specify whether to include or exclude ice roughness height data, and if so with a constant value (in metres), varying in domain, or varying in time and domain.
3.9.1.3. Specified ice concentration and thickness
3.9.1.3.1. Load a datafile which describes how the ice varies in time and domain
3.9.1.3.2. Specify a critical concentration (default = 0.9)
3.9.1.3.3. Specify whether to include or exclude ice roughness height data, and if so with a constant value (in metres), varying in domain, or varying in time and domain.

3.10. Tidal Potential

3.10.1. Specify either: (a) Exclude tidal potential, or (b) Include tidal potential (default). If included:-
3.10.1.1. Load a datafile with the harmonic constants for the tide. Required inputs are values for M2, O1, S2, K2, N2, K1, P1, Q1, Mf, Mm and Ssa, and for each the amplitude, period, nodes and arguments should be entered.

3.11. Precipitation and Evaporation

3.11.1. Specify either: (a) No precipitation and evaporation (default), (b) Specified precipitation or evaporation, or (c) Net precipitation. If b or c are specified:-
3.11.1.1. Specified precipitation and evaporation. Specify either (a) constant value (in mm/day), (b) varying in time, constant in domain, or (c) varying in time and domain. If b or c, load a data file which describes how the precipitation varies in time and/or domain
3.11.1.2. Net precipitation. Specify either (a) constant value (in mm/day), (b) varying in time, constant in domain, or (c) varying in time and domain. If b or c, load a data file which describes how the precipitation varies in time and/or domain
3.11.1.3. Specify a soft start interval (default = 0 seconds)

3.12. Wave Radiation

3.12.1. Specify either: (a) No wave radiation (default), or (b) Specified wave radiation. If b is specified:-
3.12.1.1. Load a data file which describes how the wave radiation varies in time and domain
3.12.1.2. Specify a soft start interval (default = 0 seconds)

3.13. Sources

3.13.1. Specify whether there are additional hydrodynamic sources within the model domain (default = none). If there are sources:
3.13.1.1. Specify the map projection (e.g. OSGB36, UTM, lat and long)
3.13.1.2. Specify the easting and northing of the source (in metres)
3.13.1.3. Specify if the source is (a) constant or (b) varying in time. If constant, specify the parameters below, if varying in time, load a datafile which describes how the source varies in time:-

3.13.1.3.1. Specify discharge (default = 0 m^3/s)
3.13.1.3.2. Specify u-velocity (default = 0 m^3/s) - optional
3.13.1.3.3. Specify v-velocity (default = 0 m^3/s) - optional

3.14. Structures

3.14.1. Weirs – if present:-

3.14.1.1. Specify the map projection (e.g. OSGB36, UTM, lat and long)
3.14.1.2. Load a data file specifying the location using coordinates
3.14.1.3. Specify weir type: (a) Broad crested weir, (b) Weir formula 1, or (c) Weir formula 2 (Honma)
3.14.1.4. Specify the weir dimensions, depending upon weir type:
3.14.1.4.1. Specify datum (default = 0 m) (a)
3.14.1.4.2. Specify width (default = 1 m) (a,b,c)
3.14.1.4.3. Specify crest level (default = 1 m) (a,b)
3.14.1.4.4. Specify weir coefficient (1.838 $m^{1/2}/s$) (b,c)
3.14.1.4.5. Specify weir exponent (default = 1.5) (b)
3.14.1.4.6. Specify invert level (default = 1 m) (b)
3.14.1.5. Specify if there is a valve: (a) None, (b) Only negative flow, (c) Only positive flow, or (d) No flow.
3.14.1.6. Specify alpha zero (default 0.01 m)
3.14.1.7. Specify head loss factor in terms of In Flow (default = 0.5), Out Flow (default = 1) and Free (default = 1).

3.14.2. Culverts – if present:-

3.14.2.1. Specify the map projection (e.g. OSGB36, UTM, lat and long)
3.14.2.2. Load a data file specifying the location using coordinates
3.14.2.3. Specify culvert type: (a) Rectangular, (b) Circular, or (c) Irregular
3.14.2.4. Specify the culvert dimensions, depending upon type
3.14.2.5. Specify upstream distance (default = 0 m)
3.14.2.6. Specify downstream distance (default = 0 m)
3.14.2.7. Specify length (default = 1 m)
3.14.2.8. Specify Manning's n (default = 0.013 $s/m^{1/3}$)
3.14.2.9. Specify number of culverts (default = 1)
3.14.2.10. Specify if there is a valve: (a) None, (b) Only negative flow, (c) Only positive flow, or (d) No flow.
3.14.2.11. Specify the section type: (a) Closed or (b) Open
3.14.2.12. Specify head loss factor in terms of In Flow (default = 0.5), Out Flow (default = 1), Free (default = 1) and Bends (default = 0)

3.14.3. Gates – if present:-

3.14.3.1. Specify the map projection (e.g. OSGB36, UTM, lat and long)
3.14.3.2. Load a data file specifying the location using coordinates
3.14.3.3. Specify gate type: (a) Full water column, or (b) Subset of column
3.14.3.4. Specify operation type: (a) User defined, (b) Water level or (c) Water level difference
3.14.3.5. Specify control point easting and northing (in metres)
3.14.3.6. Specify open and close levels (in metres)
3.14.3.7. Specify open and close intervals (in seconds)

3.14.4. Dikes – if present:-

3.14.4.1. Specify the map projection (e.g. OSGB36, UTM, lat and long)
3.14.4.2. Load a data file specifying the location using coordinates
3.14.4.3. Specify crest level: (a) Constant or (b) Varying in space.
3.14.4.4. Specify crest level correction: (a) Constant, (b) Constant in time and varying along curve, or (c) varying in time and varying along curve.
3.14.4.5. Specify the overtopping by either (a) Empirical formula, (b) Overtopping discharge, or (c) User-defined table:-
3.14.4.5.1. Empirical formula: specify critical level difference (default = 0.01 m) and coefficient (default = 1.838 $m^{1/2}/s$)
3.14.4.5.2. Overtopping discharge: specify constant discharge or varying in time and/or along a curve
3.14.4.5.3. User-defined table: load a datafile specifying the overtopping values

3.14.5. Piers – if present:-

3.14.5.1. Specify the map projection (e.g. OSGB36, UTM, lat and long)

3.14.5.2. Load a data file specifying the location using coordinates
3.14.5.3. Specify the pier orientation (default = 0 degrees)
3.14.5.4. Specify the streamline factor (default = 1.02)
3.14.5.5. Specify the number of sections, and for each specify the type (circular, rectangular or elliptical) and dimensions

3.14.6. Turbines – if present:-
3.14.6.1. Specify the map projection (e.g. OSGB36, UTM, lat and long)
3.14.6.2. Load a data file specifying the location using coordinates
3.14.6.3. Specify the turbine diameter (default = 16 m)
3.14.6.4. Specify the drag coefficient (default = 0.4)
3.14.6.5. Specify a correction factor, as either a constant value (default = 1), or varying in time
3.14.6.6. Optional: specify a lift coefficient, with additional parameters:-
3.14.6.6.1. Specify the orientation (default = 90 degrees)
3.14.6.6.2. Specify the maximum and minimum direction and speed of each value
3.14.6.6.3. Specify the drag and lift coefficients for each speed

3.15. Initial Conditions
3.15.1. Specify either (a) constant, (b) spatially varying surface elevation, or (c) spatially varying water depth and velocities. If b or c, load a data file listing how the following parameters vary spatially
3.15.2. Specify the surface elevation (default = 0 m)
3.15.3. Specify the u-velocity (default = 0 m/s)
3.15.4. Specify the v-velocity (default = 0 m/s)

3.16. Boundary Conditions – for each boundary specified in 1.5, choose from:
3.16.1. Land (zero-velocity) – no further parameters required
3.16.2. Specified velocities
3.16.2.1. Specify u-velocity and v-velocity (defaults = 0 m/s), either (a) constant, (b) varying in time, constant along the boundary, or (c) varying in time and along the boundary
3.16.2.2. Specify soft start parameters: time interval (default = 0 seconds), reference u-velocity and v-velocity (defaults = 0 m/s), either (a) Sinus variation, or (b) Linear variation.
3.16.3. Specified fluxes
3.16.3.1. Specify p-velocity and q-velocity (defaults = 0 $m^3/s/m$), either (a) constant, (b) varying in time, constant along the boundary, or (c) varying in time and along the boundary
3.16.3.2. Specify soft start parameters: time interval (default = 0 seconds), reference p-velocity and q-velocity (defaults = 0 $m^3/s/m$), either (a) Sinus variation, or (b) Linear variation.
3.16.4. Specified level
3.16.4.1. Specify the level (default = 0 m), either (a) constant, (b) varying in time, constant along the boundary, (c) varying in time and along the boundary, or (d) rating curve
3.16.4.2. Specify soft start parameters: time interval (default = 0 seconds) and reference level (default = 0), either (a) Sinus variation, or (b) Linear variation.
3.16.4.3. Specify whether to include a coriolis correction or not.
3.16.5. Specified discharge
3.16.5.1. Specify the discharge (default = 0 m^3/s), either (a) constant, (b) varying in time, or (c) rating curve
3.16.5.2. Specify soft start parameters: time interval (default = 0 seconds) and reference discharge (default = 0 m^3/s), either (a) Sinus variation, or (b) Linear variation.
3.16.6. Flather condition
3.16.6.1. Specify u-velocity and v-velocity (defaults = 0 m/s), either (a) constant, (b) varying in time, constant along the boundary, or (c) varying in time and along the boundary
3.16.6.2. Specify soft start parameters: time interval (default = 0 seconds), reference u-velocity and v-velocity (defaults = 0 m/s), either (a) Sinus variation, or (b) Linear variation.

3.16.6.3. Specify the level (default = 0 m), either (a) constant, (b) varying in time, constant along the boundary, (c) varying in time and along the boundary, or (d) rating curve

3.16.6.4. Specify soft start parameters: time interval (default = 0 seconds) and reference level (default = 0), either (a) Sinus variation, or (b) Linear variation.

3.16.6.5. Optional: Specify the discharge (default = 0 m^3/s), either (a) constant, (b) varying in time, or (c) rating curve. And specify soft start parameters: time interval (default = 0 seconds) and reference discharge (default = 0 m^3/s), either (a) Sinus variation, or (b) Linear variation.

3.16.6.6. Specify whether to include a Coriolis correction or not.

3.17. Decoupling

3.17.1. Specify whether or not decoupling is to be included (default = not included). If it is included:-

3.17.1.1. Specify the time step frequency (default = 1)

3.17.1.2. Load a data file which details the flux data.

3.17.1.3. Load a data file which details the area data.

3.17.1.4. Load a data file which details the specification.

3.18. Outputs

3.18.1. Choose any from the following basic parameters: surface elevation, still water depth, total water depth, u-velocity, v-velocity, p-flux and q-flux.

3.18.2. Choose any from the following additional variables: current speed, current direction, wind u-velocity, wind v-velocity, air pressure, precipitation, evaporation, drag coefficient, eddy viscosity, CFL number, convergence angle, element area.

3.18.3. Choose the data field type: (a) 2D (horizontal), (b) Mass budget, (c) Discharge, or (d) Inundation.

3.18.4. Specify whether to include: (a) the whole area (b) only the wet area, or (c) only the real wet area (the default)

3.18.5. Choose the output format: (a) area (the default), (b) line, or (c) point.

3.18.6. Specify the output file name.

3.18.7. Specify the output time steps: (a) first (default = 0), (b) last (default = 100), and (c) frequency (default = 1)

3.18.8. Specify the map projection (e.g. OSGB36, UTM, lat and long)

3.18.9. Specify the easting and northing of the required output file, for the point, line or area selected in 3.18.5

MIKE 21 Transport Module

The basic Hydrodynamic component of the model can be supplemented with additional modules. The transport module calculates the resulting transport of materials based on the flow conditions found in the hydrodynamic calculations. Below are the additional steps to include a Transport Module in a basic MIKE 21 model run:

1. Component Specification
   1.1. Specify how many components to include, and for each specify the minimum and maximum values (defaults = 0 and 10^{10})
2. Solution Technique
   2.1. Specify time integration: either (a) Higher order, or (b) low order, fast algorithm
   2.2. Specify space discretization: either (a) Higher order, or (b) low order, fast algorithm
3. Horizontal Dispersion
   3.1. Specify: (a) no dispersion, (b) dispersion coefficient formulation, or (c) scaled eddy viscosity formulation (the default).
   3.2. For dispersion coefficient formulation, specify a scaling factor (default = 0.01 m^2/s), either as a constant, varying in domain, or varying in time and domain.
   3.3. For scaled eddy viscosity formulation, specify the constant value (default = 1), either as a constant (the default), varying in domain, or varying in time and domain.
4. Decay
   4.1. Specify whether to include decay (default = not included). If it is included, specify the constant value (default = 0 /sec), either as a constant or varying in time.

5. Sources
   5.1. If a source was included in 3.13 of the MIKE HD Module, then specify either (a) specified concentration or (b) excess concentration, and specify the value (default = 0), either as a constant or varying in time.
6. Initial Conditions
   6.1. Specify the initial value (default = 0), either as a constant, or varying in domain, or varying in time and domain.
7. Boundary Conditions
   7.1. For each boundary specified in 1.5, specify the component value either (a) as a constant, (b) varying in time, constant along the boundary, or (c) varying in time and along the boundary. Also specify the soft start parameters: time interval (default = 0 seconds) and reference value (default = 0), either (a) Sinus variation, or (b) Linear variation.
8. Outputs
   8.1. Specify the output options for the component, as listed under 3.18 in MIKE 21 hydrodynamic model above.

MIKE 21 Sand Transport Module

The Sand Transport Module calculates the resulting transport of non-cohesive materials based on the flow conditions found in the hydrodynamic calculations and, if included, wave conditions from wave calculations. Below are the additional steps to include a Sand Transport Module in a basic MIKE 21 model run:

1. Model Definition
   1.1. Decide the model type: (a) Pure current (the default), or (b) wave and current.
      1.1.1. Pure current model
         1.1.1.1. Specify the transport description type: either (a) equilibrium or (b) non equilibrium (the default).
         1.1.1.2. Specify whether to include helical flow (default = not included)
      1.1.2. Wave and current model
         1.1.2.1. Generate a Sediment Table using MIKE 21 toolbox:-
         1.1.2.2. Specify the tolerance in the calculation of concentration (default = 0.0001)
         1.1.2.3. Specify the maximum number of wave periods (default = 1000)
         1.1.2.4. Specify the relative density of sediment (default = 2.65)
         1.1.2.5. Specify the critical; value of Shields parameter (default = 0.05)
         1.1.2.6. Specify the water temperature (default = 10)
         1.1.2.7. Specify whether to include or exclude the effect of ripples
         1.1.2.8. Specify whether to include or exclude bed slope
         1.1.2.9. Specify whether a deterministic or empirical bed concentration will be specified
         1.1.2.10. Specify the Gamma1 and Gamma2 parameters for wave breaking (defaults = 1 and 0.8)
         1.1.2.11. Specify the range of current speeds to be modelled (default = 0.1 to 0.6 m/s)
         1.1.2.12. Specify the range of wave heights to be modelled (default = 0.1 to 1.7 m)
         1.1.2.13. Specify the range of wave periods to be modelled (default = 5 to 7 seconds)
         1.1.2.14. Specify the range of wave heights/water depths (default = 0.01 to 0.91 m)
         1.1.2.15. Specify the range of sediment grain size (default = 0.150 to 0.350 mm)
         1.1.2.16. Specify the range of sediment grading (default = 1.1 to 1.40)
         1.1.2.17. If bed slope is included, specify the range of slopes in the current direction (default = -0.01 to +0.01) and the range of slopes normal to the current (default = -0.02 to +0.02)
   1.2. Specify whether there should be a varying layer thickness (default = no varying layer thickness). If a varying thickness is to be included, then specify the threshold thickness (default = 0.0005 m).
2. Time Parameters
   2.1. Specify a start time (default = 0)
   2.2. Specify a time step factor (default = 1)
3. Sediment Properties
   3.1. Specify a porosity (default = 0.4)

3.2. Specify a sediment grain diameter (default = 0.2 mm) and grading coefficient, σ_g (default = 1.1), either as a constant value across the domain (the default), or load a datafile specifying how the grain size varies across the domain.
3.3. If Pure Current is chosen in 1.1, then specify the relative density of the sediment (default = 2.65).

4. Bed Resistance
   4.1. Specify (a) No bed resistance, (b) Chezy number, (c) Manning Number (default = 32 $m^{1/3}/s$), (d) alluvial resistance, or (e) resistance from hydrodynamic simulation. These values can be specified as a constant, or varying in domain, or varying in time and domain. If alluvial resistance is chosen:-
      4.1.1. Specify the alluvial resistance power (default = 0)
      4.1.2. Specify the minimum alluvial resistance limit (default = 5 $m^{1/3}/s$).
      4.1.3. Specify the maximum alluvial resistance limit (default = 100 $m^{1/3}/s$).
5. Forcings
   5.1. If Pure Current is chosen in 1.1, the flow field is calculated from the hydrodynamic model. If Wave and Current is chosen in 1.1, specify the following parameters, either as a constant, or varying in time constant in domain, or constant in time varying in domain, or varying in time and domain :-
      5.1.1. Specify either a RMS wave weight or a significant wave height (default = 1 m)
      5.1.2. Specify a peak wave period or a mean wave period (default = 3 seconds)
      5.1.3. Specify a wave direction (default = 180 degrees)
6. Morphology
   6.1. Model definition
      6.1.1. Specify the maximum bed level change per day (default = 1 m/day)
      6.1.2. Specify a speedup factor (default = 1)
      6.1.3. Include or exclude feedback on hydrodynamic, wave and sand transport calculations (default = include feedback)
   6.2. Time parameter
      6.2.1. Specify the start time step (default = 0)
   6.3. Bank erosion
      6.3.1. Specify no bank erosion (the default), or if bank erosion is included:-
         6.3.1.1. Specify the angle of repose, either as a constant (default = 30 degrees), or varying in domain, or varying in time and domain
   6.4. Boundary Conditions
      6.4.1. For each boundary, specify either (a) land boundary, (b) zero sediment flux gradient (the default), or (c) zero sediment flux gradient for outflow, zero bed change for inflow.
7. Outputs
   7.1. Specify the output options, as listed under 3.18 in MIKE 21 hydrodynamic model above, with the additional options to include: total load x- and y-components, rate of bed level change, bed level change and bed level.

MIKE 21 Mud Transport Module

The mud transport module calculates the resulting transport of cohesive materials based on the flow conditions found in the hydrodynamic calculations. This module primarily models sediment with a diameter finer than 60 µm (mud), although a sand fraction can also be included which is considered to be non-cohesive. Below are the additional steps to include a Mud Transport Module in a basic MIKE 21 model run:

1. Parameter Selection
   1.1. Specify the number of grain size fractions, up to 8 (default = 1)
   1.2. Specify the number of bed layers, up to 12 (default = 1)
2. Solution Technique
   2.1. Specify time integration: either (a) Higher order (default), or (b) low order, fast algorithm
   2.2. Specify space discretization: either (a) Higher order (default), or (b) low order, fast algorithm
3. Water Column Parameters
   3.1. Sand Fractions

3.1.1. Specify whether to include or exclude sand fractions (default = exclude sand fractions). If sand fractions are in included, for each fraction specify the mean settling velocity (default = 0.001 m/s)

3.2. Deposition

3.2.1. Specify whether to apply either: (a) a Rouse Profile, together with a relative centroid height, or (b) a Teeter Profile (the default)

3.2.2. Specify the critical shear stress for each sediment fraction. Values can be specified either as a constant (default = 0.07 N/m^2), or varying in domain, or varying in time and domain.

3.3. Viscosity and Density

3.3.1. If an option other than barotrophic density is selected in the Hydrodynamic Module, specify the bulk density of the suspended sediment, and a base and reference concentration.

4. Bed Parameters

4.1. Erosion

4.1.1. Specify the maximum concentration allowed due to erosion (default = 50 kg/m^3)

4.1.2. For each sediment layer, specify whether the sediment is soft mud (default) or hard mud

4.1.3. For each sediment layer, specify the power of erosion (default = 8.3 for soft mud and 1.0 for hard mud)

4.1.4. For each sediment layer, specify the erosion coefficient, either as a constant (default = 5 x 10^{-5} kg/m^2/s), or varying in domain, or varying in time and domain.

4.1.5. For each sediment layer, specify the critical shear stress, either as a constant (default = 0.1 N/m^2), or varying in domain, or varying in time and domain.

4.2. Density of bed layer

4.2.1. For each sediment layer, specify the density, either as a constant (default = 180 kg/m^3), or varying in domain, or varying in time and domain.

4.3. Bed Roughness

4.3.1. Specify the roughness, either as a constant (default = 0.001 m), or varying in domain, or varying in time and domain.

4.4. Transition Between Layers

4.4.1. Specify whether to include or exclude transition between layers, if selected under 1.2 (default = exclude). If transition is included, specify a value either as a constant (default = 0.001 kg/m^2/s), or varying in domain, or varying in time and domain.

5. Forcings

5.1. Specify whether a wave field is defined, or to assume there are no waves (default = include wave field). If it is included, specify the following parameters either as a constant, or varying in time constant in domain, or constant in time varying in domain, or varying in time and domain :-

5.1.1. Specify the wave height (default = 1 m)

5.1.2. Specify a wave period (default = 3 seconds)

5.1.3. Specify a wave direction (default = 180 degrees)

5.2. Specify whether to include or exclude liquefaction (default = exclude). If included, specify the liquefaction factor (default = 1)

5.3. Specify a minimum water depth (default = 0 m)

5.4. Specify the shear stress formulation: either (a) Mean (Soulsby et al. 1993), (b) Max (Soulsby et al. 1993, the default), (c) Max (Fredsoe and Deigaard), or (d) Max (Fredsoe 1981)

6. Dredging

6.1. Specify whether dredging should be included (default = exclude dredging). If it is included, specify the following parameters:-

6.1.1. Specify the number of dredging operations

6.1.2. For each dredging, specify the percentage weight dredged from each sediment layer (default =equal amounts from each layer)

6.1.3. For each dredging, specify the map projection type (e.g. OSGB36, UTM, lat and long)

6.1.4. For each dredging, specify the x-coordinate

6.1.5. For each dredging, specify the y-coordinate

6.1.6. For each dredging, specify the rate of dredged mass

6.1.7. For each dredging, specify amount of spill

6.1.8. For each dredging, specify the start date and time

6.1.9. For each dredging, specify the end date and time

6.1.10. Optional: include the initial mass on the dredger (default = 0 ton), and the maximum mass on dredger (default = 10000000 ton)
6.1.11. Optional: include an update of the bed

7. Dispersion
    7.1. For each grain size fraction, specify: (a) no dispersion, (b) dispersion coefficient formulation, or (c) scaled eddy viscosity formulation (the default).
    7.2. For dispersion coefficient formulation, specify a scaling factor (default = 0.01 m^2/s), either as a constant, varying in domain, or varying in time and domain.
    7.3. For scaled eddy viscosity formulation, specify the constant value (default = 1), either as a constant (the default), varying in domain, or varying in time and domain.
8. Sources
    8.1. If a source was included in 3.13 of the MIKE HD Module, then for each grain size fraction specify either (a) specified concentration or (b) excess concentration, and specify the value (default = 0 kg/m^3), either as a constant or varying in time.
9. Initial Conditions
    9.1. Specify the initial concentration for each grain size fraction (default = 0 kg/m^3), either as a constant, or varying in domain, or varying in time and domain.
    9.2. Specify the initial layer thickness for each layer (default = m), either as a constant, or varying in domain, or varying in time and domain.
    9.3. Specify the initial percentage distribution for each layer and each grain size fraction (default = equal amounts of each fraction, and in each layer)
10. Boundary Conditions
    10.1. For each boundary specified in 1.5, specify the sediment concentration of each fraction value either (a) as a constant, (b) varying in time, constant along the boundary, or (c) varying in time and along the boundary. Also specify the soft start parameters: time interval (default = 0 seconds) and reference value (default = 0), either (a) Sinus variation, or (b) Linear variation. Alternatively, specify that there is no sediment exchange at the boundary.
11. Morphology
    11.1. Specify whether to include or exclude morphological calculations (default = exclude morphological calculations). If it is included, specify whether a speedup factor should be used (default = 1).
12. Outputs
    12.1. Specify the output options, as listed under 3.18 in MIKE 21 hydrodynamic model above, with the additional options to include for each fraction and/or bed layer: SSC, bed thickness, bed mass, settling velocity, beach shear stress, erosion, deposition, net deposition.

MIKE 21 Particle Tracking Module

The Particle Tracking module calculates the transport and determines the fate of dissolved, suspended and sedimented substances discharged or accidently spilled in lakes, estuaries and coastal areas or at the open sea. Below are the additional steps to include a Particle Tracking Module in a basic MIKE 21 model run:

1. Classes
    1.1. Specify the number of particles to track (default = 1)
    1.2. Provide a name each type
    1.3. Specify the minimum particle mass (in kg, g, mg, µg, tons or pounds)
    1.4. Specify the maximum age of the particle (in seconds)
2. Sources
    2.1. Specify the number of sources of particles (default = 1). For each source:-
    2.2. Specify either (a) it is a normal source, or (b) it is an initial source, only active before 1st time step
    2.3. Specify either (a) Point source, or (b) Area source
    2.4. Specify a source sub-type: (a) Fixed location, or (b) Moving location
    2.5. Specify the vertical position, either (a) metres above the bed, (b) metres relative to the datum, or (c) metres depth below the surface

2.6. Specify the horizontal position in terms of a map projection, x and y coodinates, or a datafile detailing a moving position,
2.7. Specify which particles defined in 1.1 to include at each source. For each particle:-
2.7.1. Specify the amount supplied by the source, either as a mass or flux, and either as a constant (default = 0 mg/s) or varying in time.
2.7.2. Specify the number of particles per time step, either as a constant (default = 20) or varying in time.
2.7.3. Specify whether the mass or flux applies to the total amount emitted, or per particle
3. Decay
3.1. Specify whether to include decay for each particle type (default = included). If it is included, specify the value, either as a constant (default = 0 /sec) or varying in time.
4. Settling
4.1. Specify the settling velocity, either as a constant (default = 0.1 m/s) or varying in time.
4.2. Optional: include flocculation. If included:-
4.2.1. Specify the minimum concentration for flocculation (default = 0.01 mg/m^3)
4.2.2. Specify the maximum concentration for flocculation (default = 10 mg/m^3)
4.2.3. Specify alpha (default = 1)
4.3. Optional: include hindered settling. If included:-
4.3.1. Specify the Gelling Point (default = 50 mg/m^3)
4.4. Optional: include salinity. If included:-
4.4.1. Specify the C1 parameter (default = 0.5)
4.4.2. Specify the C2 parameter (default = -0.33)
5. Dispersion
5.1. Horizontal dispersion
5.1.1. For each particle type, specify: (a) no dispersion, (b) dispersion coefficient formulation, or (c) scaled eddy viscosity formulation (the default).
5.1.2. For dispersion coefficient formulation, specify a scaling factor (default = 0.01 m^2/s), either as a constant, varying in domain, or varying in time and domain.
5.1.3. For scaled eddy viscosity formulation, specify the constant value (default = 1), either as a constant (the default), varying in domain, or varying in time and domain.
5.2. Vertical dispersion
5.2.1. For each particle type, specify: (a) no dispersion, (b) dispersion coefficient formulation, or (c) scaled eddy viscosity formulation (the default).
5.2.2. For dispersion coefficient formulation, specify a scaling factor (default = 0.01 m^2/s), either as a constant, varying in domain, or varying in time and domain.
5.2.3. For scaled eddy viscosity formulation, specify the constant value (default = 1), either as a constant (the default), varying in domain, or varying in time and domain.
6. Erosion
6.1. For each particle type, specify whether to include erosion (default = not included). If it is included, specify the critical shear stress (default = 0.001 N/m^2), either as a constant or varying in domain, or varying in time and domain.
7. Drift Profile
7.1. Optional: use bed shear profile
7.1.1. Specify the kinematic viscosity (default = 1.14 x 10^{-6} m^2/s)
7.2. Optional: use surface wind acceleration
7.2.1. Specify wind weight (default = 0.1)
7.2.2. Specify the wind drift direction (default = 28 degrees)
7.2.3. Specify the kinematic viscosity (default = 1.14 x 10^{-6} m^2/s)
7.3. Optional: use wind induced profile
7.3.1. Specify wind drift (default = 0.03)
7.3.2. Specify the depth of influence (default = 100 m)
7.3.3. Specify the distance offshore (default = 100 m)
8. Salinity
8.1. Specify whether calculate salinity from the hydrodynamic model (the default), or specify the salinity directly. If it is specified directly, specify the salinity either as a constant (default = 20 PSU), or varying in time, or varying in time and domain.
9. Bed Roughness
9.1. Specify whether calculate bed roughness from the hydrodynamic model (the default), or specify the bed roughness directly. If it is specified directly, specify either as a constant (default = 0.001 m), or varying in domain, or varying in time and domain.

10. Wind Forcing
    10.1. Specify either: (a) no wind, (b) user specified wind, or (c) wind from hydrodynamic model. If user specified wind is selected:-
        10.1.1. Specify wind speed and direction, either as a constant, or varying in time, or varying in time and domain
        10.1.2. Specify a soft start interval (default = 0 seconds)
11. Outputs
    11.1. Specify the output options, as listed under 3.18 in MIKE 21 hydrodynamic model above, with the additional options to include for each particle type: total amount, suspended amount, sedimented amount, specified z-range (provide depth, height or datum levels).

MIKE 3 Flow Model FM

MIKE 3 Flow Model FM is a 3-dimensional version of the MIKE 21 modelling system with data calculated from and output onto a flexible mesh. The modelling system has the same basic assumptions and processes as MIKE 21, but for time integration a semi-implicit approach is used where the horizontal terms are treated explicitly and the vertical terms are treated implicitly.

A run listing for a MIKE 3 Flow Model

MIKE 3 FM has a very similar flow list to that given earlier for MIKE 21 FM. The following lists the additional parameters required to run a MIKE 3 simulation:

1. Domain
    1.1. Specify the type of vertical mesh to use: either (a) sigma, or (b) combined sigma and z-level
    1.2. Specify the number of layers (default = 10)
    1.3. Specify the thickness of each layer (default = 0.01 m)
2. Sources
    2.1. If there are sources: specify the parameters listed for MIKE 21 for each layer defined in 1.2 above.
3. Initial Conditions
    3.1. In addition to the parameters listed for MIKE 21, specify the ws-velocity (default = 0 ms)
4. Boundary Conditions
    4.1. In addition to the parameters listed for MIKE 21, for specified velocities, fluxes or discharges, specify either (a) a uniform vertical profile, or (b) logarithmic vertical profile.
5. Outputs
    5.1. In addition to the options for MIKE 21, there is a choice of 3D field type.
    5.2. For a 3D output, the following reduced set of basic parameters are available: u-velocity, v-velocity, w-velocity and ws-velocity

MIKE 21 Spectral Waves FM

MIKE 21 Spectral Waves (SW) Model FM is a modelling system with data calculated from and output onto a flexible mesh. The model simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas.

The modelling system includes two formulations: (a) directional decoupled parametric formulation, based on a parameterization of the wave action conservation equation, as described by Holthuijsen (1989); (b) fully spectral formulation, based on the wave action conservation equation, as described in e.g. Komen et al. (1994) and Young

(1999), where the directional-frequency wave action spectrum is the dependent variable.

A run listing for a MIKE 21 Spectral Waves Model

The following flow list details the required steps to prepare a MIKE 21 Spectral Waves Model, and lists the input parameters required at each stage:

6. Domain
    - 6.1. Load the bathymetry mesh previously created in MIKE ZERO (1.12 above).
    - 6.2. Specify the map projection type (e.g. OSGB36, UTM, lat and long)
    - 6.3. Specify a minimum depth cutoff (default = highest elevation in the dataset)
    - 6.4. Specify a datum shift (default = 0 m)
    - 6.5. Provide a recognizable name to each open boundary in the bathymetry dataset
7. Time
    - 7.1. Specify the number of time steps to compute (default = 100)
    - 7.2. Specify the time step interval (default = 30 seconds)
    - 7.3. Specify a simulation start date and time (default = 01/01/2004 00:00:00)
    - 7.4. Specify a simulation end date and time (default = 01/01/2004 00:50:00)
8. Basic Equations
    - 8.1. Specify the spectral formulation: either (a) directionally decoupled parametric formulation, or (b) fully spectral formulation (the default)
    - 8.2. Specify the time formulation: either (a) quasi stationary formulation, or (b) instationary formulation (the default)
9. Spectral Discretization
    - 9.1. If fully spectral formulation was chosen in 3.1, specify the frequency discretization: either as (a) equidistant, or (b) logarithmic, and specify the number of frequencies (default = 25), the minimum frequency (default = 0.005 Hz) and frequency interval (default = 0.02 Hz)
    - 9.2. Specify the number of directions in the directional discretization (default = 16)
    - 9.3. If fully spectral formulation was chosen in 3.1, specify whether to include a separation of wind sea and swell, and if so specify (a) threshold frequency (default = 0.125 Hz), or (b) dynamic threshold frequency (default = 0.5959088 Hz)
10. Solution technique
    - 10.1. Specify the geographical space discretization: either (a) higher order, or (b) low order, fast algorithm (the default)
    - 10.2. Specify the maximum number of levels in transport calculation (default = 32)
    - 10.3. Specify the number of steps in source calculation (default = 1)
    - 10.4. Specify the minimum time step (default = 0.01 seconds)
    - 10.5. Specify the maximum time step (default = 30 seconds)
11. Water Level Conditions
    - 11.1. Specify either (a) no water level variation, or (b) specify water level variation (the default). If the water level is to be specified:-
        - 11.1.1. Specify the water level, either as a constant (default = 0 m), or varying in time, or varying in time and domain
        - 11.1.2. Specify a soft start (default = 0 seconds)
12. Current Conditions
    - 12.1. Specify either (a) no current variation, or (b) specify current variation (the default). If the current is to be specified:-
        - 12.1.1. Specify a blocking factor (default = 0.1)
        - 12.1.2. Specify the x- and y- current velocities, either as constants (default = 0 m/s), or varying in time, or varying in time and domain. These inputs could have been determined previously from a MIKE 21 Hydrodynamic Model run.
        - 12.1.3. Specify a soft start (default = 0 seconds)
13. Wind Forcing
    - 13.1. Specify either: (a) Exclude wind forcing (default), or (b) include wind forcing. If wind forcing is included, specify either (a) constant, (b) varying in time, constant in domain, or (c) varying in time and domain:-
        - 13.1.1. Specify wind speed (default = 0 m/s)

13.1.2. Specify wind direction (default = 0 degrees)
13.1.3. Specify soft start interval (default = 0 seconds)
13.1.4. Specify the type of air-sea: either (a) uncoupled, or (b) coupled (the default). Also specify the Charnock parameter (default = 0.01)

14. Ice Coverage
    14.1. Specify either: (a) No ice coverage (default), (b) specified ice coverage. If included:-
        14.1.1. Load a datafile which describes how the ice varies in time and domain
        14.1.2. Specify the coverage (default = 0.33)
        14.1.3.
15. Diffraction
    15.1. Specify either (a) no diffraction (the default), or (b) diffraction included. If included:-
        15.1.1. Specify a smoothing factor (default = 1)
        15.1.2. Specify the number of smoothing steps (default = 1)
16. Energy Transfer
    16.1. Specify whether to include or exclude quadruplet-wave interaction (default = include)
    16.2. Specify whether to include triad-wave interaction with a transfer value (default = exclude)
17. Wave Breaking
    17.1. Specify either (a) no wave breaking, or (b) wave breaking included (the default). If included:-
        17.1.1. Specify either (a) constant gamma (default = 0.8), or (b) functional form (Ruessink et al. 2003), or (c) Functional Form (Nelson 1987,1994)
        17.1.2. Specify an alpha value (default = 1)
18. Bottom Friction
    18.1. Specify either (a) no bottom friction, (b) friction coefficient, (c) friction factor, (d) Nikuradse roughness (default = 0.04 m), or (e) sand grain size. Also specify a current friction (default = 0)
19. White capping
    19.1. Specify either (a) no white capping, (b) include white capping (the default). If included:-
        19.1.1. Specify the dissipation coefficient, either as a constant (default = 4.5), varying in domain, or varying in time and domain
        19.1.2. Specify the dissipation coefficient, either as a constant (default = 0.5), varying in domain, or varying in time and domain
        19.1.3. Specify the wave power for mean angular frequency (default = -1)
        19.1.4. Specify the wave power for mean wave number (default = -1)
        19.1.5. Specify the type of spectrum: either (a) wind sea part (the default) or (b) whole spectrum
        19.1.6.
20. Structures
    20.1. Point Structures
        20.1.1. Specify the location and dimension of any point structures
    20.2. Lines Structures
        20.2.1. Specify the location and dimension of any line structures
        20.2.2. Specify the either (a) constant transmission type or (b) Goda's type
        20.2.3. Specify the coefficient (default = 1)
        20.2.4. Specify the Alpha (default = 2.2)
        20.2.5. Specify the Beta (default = 0.4)
        20.2.6. Specify the Minimum coefficient (default = 0)
        20.2.7. Specify the Maximum coefficient (default = 1)
        20.2.8. Specify either (a) constant reflection coefficient, with the coefficient (default = 0), or (b) full reflection.
21. Boundary Conditions - for each boundary specified in 1.5, choose from:
    21.1. Closed boundary – no further parameters needed
    21.2. Lateral boundary – no further parameters needed
    21.3. Reflective boundary – specify reflection coefficient
    21.4. Wind-sea and swell wave parameters – for all waves, or wind-sea and/or swell waves, specify the following, either as a constant, or varying in time, constant along the boundary, or varying in time and along the boundary:-
        21.4.1. Specify significant wave height (default = 1 m)
        21.4.2. Peak wave period (default = 8 seconds)
        21.4.3. Mean wave direction (default = 270 degrees)
        21.4.4. Directional spreading index or standard deviation (default = 5 degrees)

        21.4.5. Specify a soft start time interval (default = 0 seconds)
        21.4.6. Specify a soft start reference significant wave height (default = 0 m)
    21.5. Wave action spectrum or wave energy spectrum
        21.5.1. Load a datafile detailing the spectrum

22. Outputs
    22.1. Choose outputs for either (a) all waves, (b) wind-sea waves, or (c) swell waves.
    22.2. Choose outputs for either (a) whole wave spectrum, (b) a frequency range (c) a directional range, or (d) a directional and frequency range
    22.3. Choose any from the following parameters: significant wave height, maximum wave height, wave period (peak, T1, T2, or Tm10), peak wave direction, mean wave direction, directional standard deviation, wave velocity components, radiation stresses, particle velocities, wave power.
    22.4. Specify whether to include: (a) the whole area (b) only the wet area, or (c) only the real wet area (the default)
    22.5. Choose the output format: (a) area, (b) line, or (c) point (the default).
    22.6. Specify the output file name.
    22.7. Specify the output time steps: (a) first (default = 0), (b) last (default = 100), and (c) frequency (default = 1)
    22.8. Specify the map projection (e.g. OSGB36, UTM, lat and long)
    22.9. Specify the easting and northing of the required output file, for the point, line or area selected in 3.18.5

APPENDIX D

LIST OF ACRONYMS AND ABBREVIATIONS

ABP – Associated British Ports
ABPmer – ABP Marin Environmental Research
ADCP – Acoustic Doppler Current Profiler
AOEMP – Adaptive Operational Environmental Management Plan
AIAA – American Institute of Aeronautics and Astronautics
AWAC – Acoustic Wave and Current (measurement device)
BGS – British geological Survey
BMT – British Maritime Technology
BSS – Brier Skill Score
BW – Boussinesq Waves
Cefas – Centre for Environment, Fisheries and Aquaculture Studies
CEMP – Construction Environment Management Plan
CFFS – Coastal Flood Forecasting System
CFD – Computational Fluid Dynamics
DEFRA – Department for Environment, Food and Rural Affairs
DHI – Danish Hydraulics Institute
DEMP – Decommisisoning Environmental Management Plan
DOE – Department of Environment
DST – Decision Support Tool
DTM – Digital Terrain Model
EA – Environment Agency
EDF – Electricite de France
EGA – Expert Geomorphological Assessment
EIA – Environmental Impact Assessment
EPA – Environmental Protection Agency (USA)
ERP – Estuaries Research Programme
FD – Finite Difference
FE – Finite Element
FEMA – Federal Emergency Management Authority (USA)
FM – Flexible Mesh
FV – Finite Volume
FWR – Foundation for Water Research
GIS - Geographical Information System
GPS – Global Positioning System
HD – Hydrodynamics
HRA – Habitats Regulations Assessment
HTA – Historical Trend Analysis
IPC – Infrastructure Planning Commission
KPAL – Kenneth Pye Associates Ltd
LiDAR – Light Direction and Ranging
LTM – Long-Term Morphological Model
MAS – Most Adverse Scenario
MEDIN – Marine Environmental Data and Information Network
MSESS – Mean Square Error Skill Score
MT – Mud Transport (module)
MTM – Medium Term Morphological Model
NE – Natural England
NOAA – National Oceanographic and Atmospheric Administration (USA)
NOC – National Oceanography Centre
NSIP – Nationally Significant Infrastructure Plan

NRW – Natural Resources Wales
NTSLF – National Tidal and Sea Level Facility
PSMSL – Permanent Service for Mean Sea Level
PT – Particle Tracking (module)
RMS – Root Mean Square
RTK – Real Time Kinematic
SEA – Strategic Environmental Assessment
SEPA – Scottish Environmental Protection Agency
SSC – Suspended Sediment Concentration
ST – Sand Transport (module)
SW – Spectral Waves
UK – United Kingdom
UKCP – UK Climate Programme
UKHO – UK Hydrographic Office
USACE – US Army Corps of Engineers
WFD – Water Framework Directive
WRc – Water Research Centre

Data Archive Appendix

No data outputs were produced as part of this project.

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