Forecasting Extreme Water Levels in Estuaries for Flood Warning.

Stage 2: Review of External Forecasts and Numerical Modelling Techniques

R&D Project Record W5/010/2

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Statement of use
This report describes the second stage of a study aiming to improve the Agency's flood warning systems in estuaries, and complements the work previously described in Project Record W5/010/1. It consists of an overview of the currently available models that can be used for the prediction and forecasting of extreme water levels. It also covers an assessment of the accuracy of existing methods applied at sites in two Agency Regions. The report is supplied for information only, prior to the project entering its final stages in which it is intended that improved methodology will be recommended for use by the Agency. The report will be of interest mainly to those flood defence staff specifically involved in providing flood warnings in estuaries.

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EXECUTIVE SUMMARY

The first Interim Report covering Stage 1 of the Study consisted of a review of current practice and recommendations for work to be carried out in subsequent stages. In particular the Stage 1 Report contained a detailed review of current practice for tidal flood forecasting in England and Wales.

The primary aim of this second Interim Report focuses on a review of "external forecasts" which, in the context of flood forecasting in estuaries for flood warning purposes in England and Wales, relate to storm tide forecasting. An overview of existing operational procedures was included in the Stage 1 review (Section 2.3 of the Stage 1 Interim Report). Section 2 of this report covers operational storm tide forecasting in the UK plus a review of other operational systems in Europe. It benefits from a direct input from the Proudman Oceanographic Laboratory (POL). More detailed information on UK storm surge predictions has been commissioned from POL and will be incorporated as it becomes available.

The report also covers an assessment of the accuracy of existing methods as applied operationally at sites identified in the North West and South West Regions of the Environment Agency for England and Wales. The detailed analysis undertaken is contained in Technical Appendices (Appendices 1 and 2) with the main body of the Report focussing on a review of the current practice form Storm Tide Forecasting and the available literature in the area of forecasting extreme water levels in estuaries for flood warning. The review is a preliminary effort that will be refined after further guidance has been provided by POL and other information has been collected during the remaining duration of the Project.

This Report provides a more general review of numerical methods, especially as employed in estuaries, and exposes some of their fundamental limitations. This section focuses primarily on the problems of numerical modelling and is based mainly on the work of Scott (1996) who formally worked as a member of the Research Group prior to it relocating to the University of Bristol from the University of Salford.

A preliminary review of the available literature on the numerical modelling of estuaries is also included. A limited body of literature concerning the development and application of numerical methods for modelling water movement exists. As new areas are developed in which numerical modelling may be beneficial, and as computing power increases to allow ever more detailed and complex simulations, further research will doubtless occur. It is not the purpose of this review to provide a comprehensive catalogue of numerical modelling techniques for shallow water flow. Rather it is intended to give an overview of modelling and to detail the research which has been done in the relatively less well-developed field of estuary flooding. Unfortunately, the literature available on operational applications is rather sparse with the United Kingdom and The Netherlands being the primary areas of activity.

KEY WORDS

Numerical methods; characteristics; finite difference; finite element; grid generation; tidal propagation; shallow water equations; curvilinear; tidal surge; fluvial flood forecasting.

1. INTRODUCTION

1.1 Objectives and Layout

The overall objective of the study is to develop rigorous but practicable methods for the real-time forecasting of extreme water levels in estuaries, suitable for incorporation into existing Environment Agency flood warning systems.

"Estuary" is defined in the Oxford English Dictionary as "the tidal mouth of a large river". For the purposes of this research we propose that the definition include all rivers for which the Agency has a possible flood warning role. This report will consider the boundaries of a particular estuary to be from a point where the tidal effect starts to have a significant effect on water levels at the upstream end, to a point where the fluvial flow or the estuary shape has an insignificant effect on water levels at the downstream end.

The primary aim of this Report focuses on a review of "external forecasts" which, in the context of flood forecasting in estuaries for flood warning purposes, relate to storm tide forecasting. Section 2 of the report covers operational storm tide forecasting in the UK plus a review of other operational systems in Europe. Section 3 is a review of numerical modelling, especially as applied to estuaries. Concluding remarks are made in Section 4. The report also covers an assessment of the accuracy of existing methods as applied operationally at sites identified in the North West and South West Regions of the Environment Agency for England and Wales. The detailed analysis undertaken is contained in Technical Appendices (Appendices 1 and 2).

1.2 Background

The Environment Agency (Agency) has direct responsibility for flood defence and flood warning in England and Wales. This responsibility includes the provision and maintenance of suitable flood defences and the production of flood warnings for the estuaries of England and Wales.

The forecasting of water levels in estuaries is a complicated process due to the interaction of local tides with river flows, winds and waves. Currently there is a lack of an appropriate methodology (or methodologies) and inadequate data for the confident forecasting of extreme water levels in estuaries. This project was born out of the need to address these problems to ensure the Agency can comprehensively satisfy its flood warning duties.

The project is a three year National R&D study, scheduled for completion by 31 March 2001, that will examine the methods currently used for the forecasting of estuary water levels and develop improved techniques. This is the second report for this project. The first report (R&D Project Report W5/010/1) contained the findings of the initial phase of the project aimed at reviewing the methods currently adopted and the data available to Agency flood warning staff.

2. OPERATIONAL TIDAL SURGE MODELLING

2.1 Introduction

With the likelihood of significant climate change impacts on the generation of future storm surges it seems sensible to review the current state of modelling of tidal surges across Europe. Changes in the sea level are primarily due to variations in the gravitational attraction of the sun and moon. Additionally, the effect of global temperature rise will have a direct impact on the thermal expansion of the water body whilst increased storminess will introduce increased wind stress and barometric pressure effects. Bode and Hardy (1997) recently reviewed developments in storm surge modelling and the PROMISE project (see URL: http://www.pol.ac.uk/promise/) which is targeted at rationalising existing operational models, also provides an overview of current operational practice in Europe.

2.2 Tide, Surge and Wave Dynamics

Tides and storm surges are described by the so-called “long wave equations” (see e.g. Bode and Hardy, 1997). A fundamental assumption is that wavelengths are large compared with the water depth. Tides are generated by gravitational forces acting over the whole water column in the deep ocean. They propagate as waves and are dissipated by bottom friction in shallow water on continental shelves. Local enhancements can occur due to shape effects producing very large tides.

Storm surge generation is represented by two terms in these equations; wind stress/water depth, and the horizontal gradient of atmospheric pressure at the sea surface. The wind effect depends on water depth and increases as the depth decreases whereas the pressure effect is independent of depth. The most important mechanism for surge generation is wind stress acting over shallow water. In deep water, surge elevations are approximately hydrostatic; a 1 HPa decrease in atmospheric pressure gives about 1 cm increase in surge elevation from p = ñgh.

Surges are superimposed on the normal astronomical tides. Where the tidal range is large, the relative timing of a surge peak and tidal high water is critical. The nature of the flooding problem in estuaries due to the combined effects of storm surge + astronomical tide + fluvial flood + local effects is complex. Severe flooding usually only results from the coincidence of two or three of these causal factors (outlined in Figure 2.1). A moderate storm surge, which in itself is not a problem, when combined with a spring tide peak may be devastating. Likewise coincidence with a rare fluvial flood or a particularly severe combination of local effects (e.g. local wind stress/depth, shape or bathymetric impact) may cause a catastrophe. In addition the occurrence of a strong storm surge is likely to coincide with strong wave impact where overtopping of local coastal flood defences may occur. The forecasting of what is a combination of extremes is fundamentally difficult and by definition rare. This is the primary reason for the current lack of data on past performance of operational models within the EA at the present time.

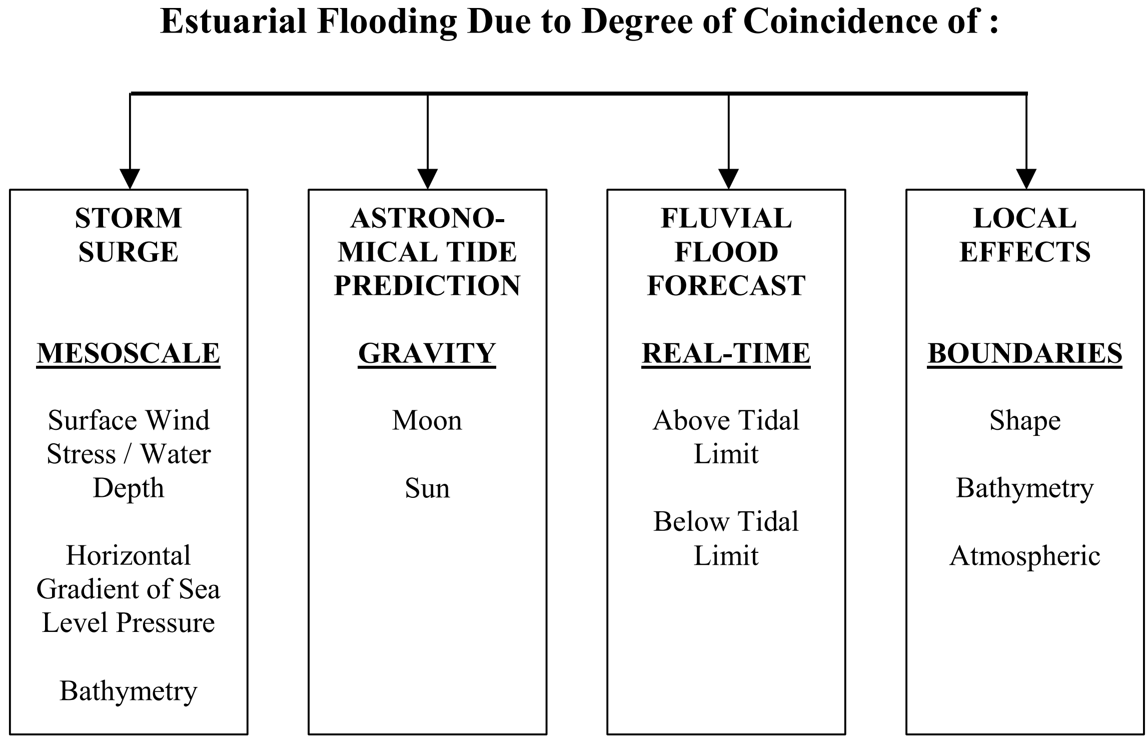

Figure 2.1 Factors Affecting Estuarial Flooding

North West Europe contains a wide range of oceanographic regimes. Resonance produces large tides in the Bristol Channel, the Gulf of St. Malo and the eastern Irish Sea, which dominate their dynamics, whereas tides in the Baltic and Mediterranean are small. The North Sea is large enough to support propagating (as long waves) tides and storm surges. Surges generated north and west of Scotland can travel into the North Sea, south along the east coast of England returning along the Dutch, German and Danish coasts. These are known as externally generated or “external” surges. Extensive areas of very shallow water susceptible to large locally generated (“internal”) storm surges occur in the German Bight. In contrast the Iberian peninsular has narrow shelves bounded by deep ocean so surges contain a significant hydrostatic pressure generated component modified by the local effects of coastal winds.

2.3 Overview of UK Tide and Surge Forecasting System

The Met Office has run 2D tide-surge models developed by the Proudman Oceanographic Laboratory routinely since 1978 (Flather, 1979, Flather *et al.* 1991). The present model, CS3, introduced in 1991, covers the NW European shelf (12ºW to 13ºE, and 48º to 63ºN) with resolution 1/6º in longitude by 1/9º in latitude, ~12km. It has open boundary input of 15 tidal harmonics and an external surge component, assumed hydrostatic. Tide generating forces and the drying and flooding of inter-tidal areas are accounted for. The model is driven by wind and surface atmospheric pressure data from the Met Office’s limited area atmospheric model (LAM), with resolution about 50km and 1 hour. Two runs are carried out each day, comprising a hindcast from T-12 to T+00, and a forecast covering T+00 to T+36 hours. The hindcast runs are forced by met data from the atmospheric model assimilation cycle, incorporating met observations. [In mid-July 1999, the LAM forcing was replaced by data from a new meso-scale atmospheric model on a rotated latitude-longitude grid of 0.111º (~12 km). Four surge model runs per day are carried out, each comprising a 6 hour hindcast + 36 hour forecast.] The model is used to predict the storm surge component, accounting for interaction with the tides, by subtracting the model predicted tide from the tide with surge solution. This is added to the harmonically predicted tide based on tide-gauge observations to estimate total water level.

Results are used by the UK Storm Tide Forecasting Service and the Environment Agency (EA) as the basis for flood warnings on the coasts of England and Wales. The UK National Tide Gauge Network consists of gauges at about 35 sites, from which data are retrieved in near real-time to check forecast accuracy and for assimilation. The model forecast accuracy achieved varies for different parts of the coast - typically ~10 cm (RMS).

Additional models have also been introduced to address specific problems. Shelf-scale models did not provide useful surge forecasts for the Bristol Channel, with its large tidal range and strong interactions. This led to the development of a system of 1-way nested local models with 4km and 1.3 km grids linked to a 1D model of the River Severn. These models use boundary tidal input of 26 harmonics and surge components interpolated from the shelf model. Because the tide-surge interactions are so strong, separation of the surge component is difficult. The resulting surge in the upper Channel also exhibits rapid changes around the time of tidal high water, causing problems with interpretation of the results for flood warning. Tuning of the models (Amin and Flather, 1996) provided accuracy for tidal prediction comparable with that of the harmonic method and allowed the models to be used to predict directly total water levels.

To provide surge forecasts necessary for operation of the Thames Barrier, a 2D model of the southern North Sea and eastern English Channel, linked to a 1D model of the River Thames was set up by POL in 1989 and is run by the EA at the Barrier site. Open boundaries are at 55ºN, 5ºE, and at 2ºW. A simple non-optimal assimilation scheme – the “boundary correction method” (Flather, 1984) – uses data from the tide gauges at North Shields and Newhaven to correct errors in open boundary surge input taken from operational shelf model runs carried out at the Met Office. This gives a useful improvement in surge forecast accuracy during the ~9 hour propagation time from the boundary to the Barrier; the lead-time required for decisions on closure. (N.B. The 1D POL model is currently being replaced by a 1D ISIS model of the tidal Thames.)

A larger English Channel – North Sea model (ECNS) uses a similar approach to assimilate data from the tide gauges at Aberdeen and Newlyn. This model has been run at the Met Office for the last 3 years.

The UK has a long coastline with varied tide and surge conditions. Further local models for complex sections have been developed but not yet implemented operationally. Major surge events are generally well handled and moderate surges on large spring tides cause more forecast and warning errors. Some cases, with external surges travelling south along the east coast of England during periods of south-west winds, have been problematic. Figure 2.2 shows predictions of a typical external surge in November 1998 from the UK operational model archive. Flather and Smith (1993) investigated the causes of a significant under-prediction of surges on the east coast and in the Thames Estuary in January 1993. They showed that a small perturbation near the Wash in the south-west winds was not forecast by the atmospheric model. As a result, model offshore winds were too strong and the predicted surge was too small. In this case the error was generated within the forecast, not from initial conditions, and reached coastal points within a short time. Such errors are difficult to correct. Even the most sophisticated assimilation schemes may be ineffective in such situations.

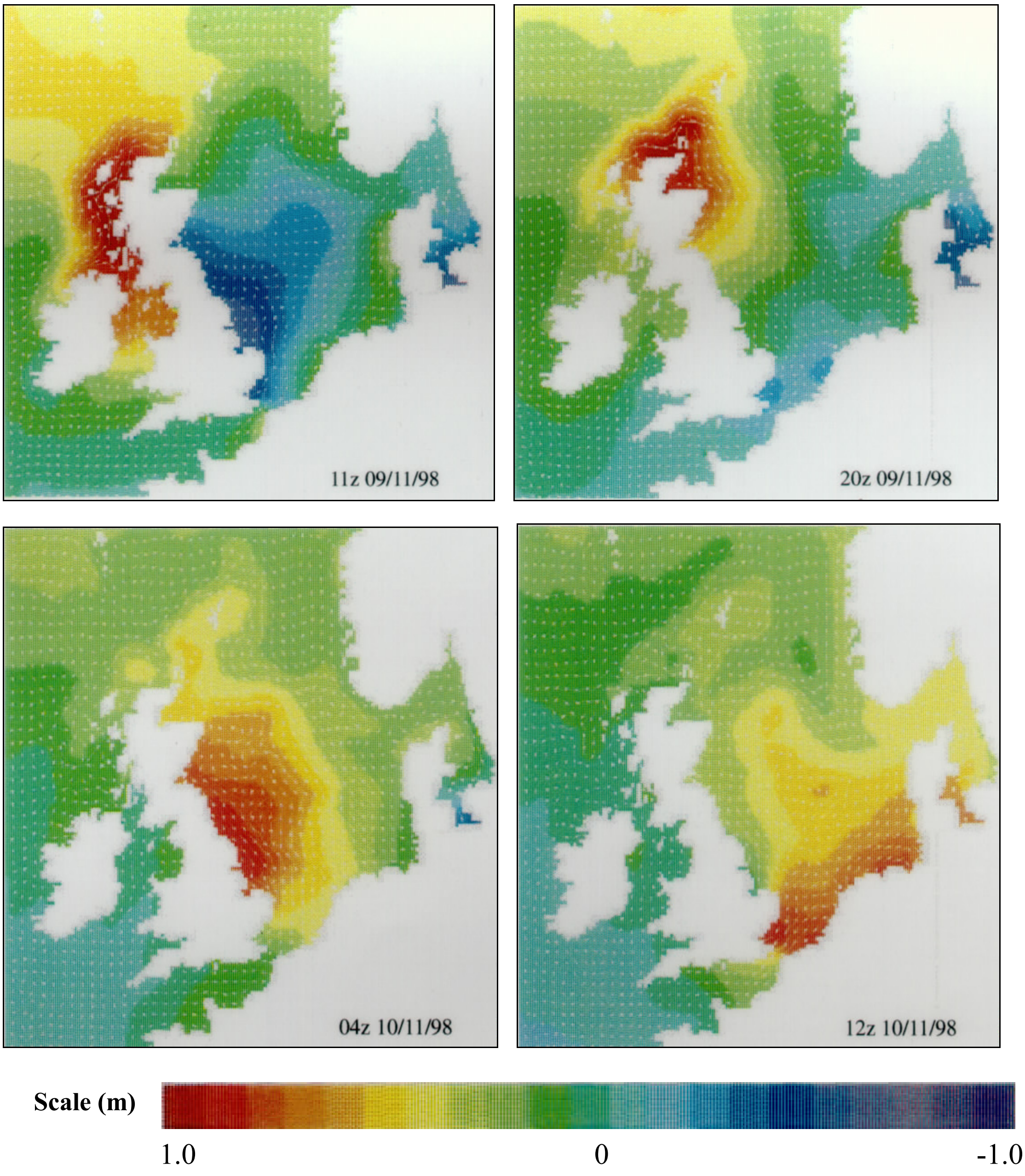

Figure 2.2A Typical External Surge Event from the UK Operational Storm Surge Model Archive, Showing Surge Generation West of Scotland, Followed by Propagation Around the North of Scotland and Southwards Along the East Coast of England into the Southern Bight of the North Sea (source: Flather (2000))

2.4 Overview of Other Operational Systems

2.4.1 Norway - Tides and Storm Surges

At the Norwegian Meteorological Institute (DNMI), the three-dimensional ocean model ECOM (Estuarine, Coastal and Ocean Model), a version of the Princeton Ocean Model, is used to forecast storm surges and currents (Engedahl, 1995). The model is run on a 20km Cartesian grid on a polar stereographic projection covering most of the NW European continental shelf, the eastern Norwegian Sea, & the Barents Sea. For storm surge prediction, ECOM is run in 3D barotropic mode (with 12 "sigma" levels in the vertical); a 3D baroclinic run with 17 sigma levels provides currents (mainly for input to an oil drift model), together with sea surface elevation, temperature and salinity. Runs are carried out twice a day, at 00 and 12 UTC, to produce forecasts to T+48 hours. The forcing consists of fields of 10 m wind and atmospheric pressure at MSL provided six hourly at 50 km resolution by the operational HIRLAM weather prediction model at DNMI. Each forecast is preceded by an 18 hour hindcast forced by six hourly analysed fields from HIRLAM, giving a total simulation time of 66 hours per run.

On lateral open boundaries, both model runs are forced by multi-year monthly mean climatological fields of sea level and currents. At present, the tides are not included. The 3D baroclinic run is also forced by climatological salinity and temperature at the boundaries, and includes monthly mean fresh water inputs from the Baltic and the major European rivers. To prevent the model results from becoming unrealistic, the prognostic fields of salinity and temperature are relaxed towards the climatological mean in the deeper parts (below approximately 500 m). At the surface the fluxes of salinity and temperature are controlled by relaxation (nudging) using climatological mean surface values. All operational forecasts are run on sequential or parallel (CRAY J90 / CRAY T3E) computers in Trondheim.

2.4.2 Denmark - Tides and Storm Surges

Since 1990, the Danish Meteorological Institute (DMI) has run a nested system of 2D models based on "System21", developed at the Danish Hydraulics Institute. This covers the North Sea, Skagerrak, Danish Belts and the Baltic with grid resolutions of about 18km, 6km and 2km (Figure 2.3). Forecasts covering the period T+00 to T+36 hours are run twice each day to predict sea levels for coastal flood warning along the Danish coast (in particular the Danish Wadden Sea). Forecasts start at T = 00 UTC and 12 UTC and are preceded by a 24 hr or 36 hr hindcast starting at 00 UTC on the previous day. Extended water level and current prediction runs for T+00 to T+120 hours were carried out during construction of the Great Belt Link. The 36 hour forecasts are driven by 10 m winds and MSL atmospheric pressure from the DMI version of HIRLAM, with 0.15° and 1 hour resolution, but for the extended 5-day forecasts UK Met Office LAM data at 1.25° and 6-hour resolution are used.

On open boundaries (Scotland to Norway and in the Dover Strait) 10 tidal constituents (no surge) are introduced. Twenty-two Danish tide gauges provide data for validation. In addition, data from 4 British and 6 Swedish stations are used for monitoring and calibration. Vested *et al.* (1995) describe the system and accuracy achieved. Average RMS errors over all stations and for operational forecasts 6 – 18 hours ahead are about