Coastal flood risk – from storm surge and waves to inundation

LANDF♦RM event: E11501

Report of a workshop organised by the Flood Risk Management Research Consortium and LANDF♦RM held at CIRIA, Classic House, 174-180 Old Street, London on 26th May 2011

Speakers	Chris Wilson	National Oceanography Centre
	Nicolas Chini	University of Manchester
	Maurice McCabe	University of Manchester
	Alistair Borthwick	University of Oxford
Chairman	Peter Stansby	University of Manchester

INTRODUCTION

This report summarises presentations and discussion at a dissemination workshop organised by the Local Authority Network on Drainage and Flood Risk Management (LANDF♦RM) in conjunction with the Flood Risk Management Research Consortium (FRMRC). LANDF♦RM is a platform for those working in and with local authorities to share information regarding flood risk management. FRMRC provides leading edge research on flood risk management and aims to increase understanding of flooding processes, generate new and original science, and support improved management of flood risk. This includes addressing the challenges of delivering accurate forecasting of floods, as well as identifying and reducing flood risks to people, property, and the environment. The FRMRC consists of universities working alongside stakeholders in the public and private sectors. The group's breadth of interests and multi-disciplinary research adds considerable value to existing knowledge about flooding processes.

The aims of the workshop were to provide (a) an understanding of coastal processes of wind, waves, tides, and storm surges, along with the impact of climate change, (b) insights into an approach to predict overtopping and inundation, including associated implications for flood management, and (c) an opportunity to share experiences with other professionals facing similar challenges.

THE ISSUES

Chairman Peter Stansby of the University of Manchester opened the workshop and provided an outline of the issues to be discussed. These were illustrated through a road map summarising work to date within the coastal theme of FRMRC's research and how the components of that research fit together: see Figure 1.

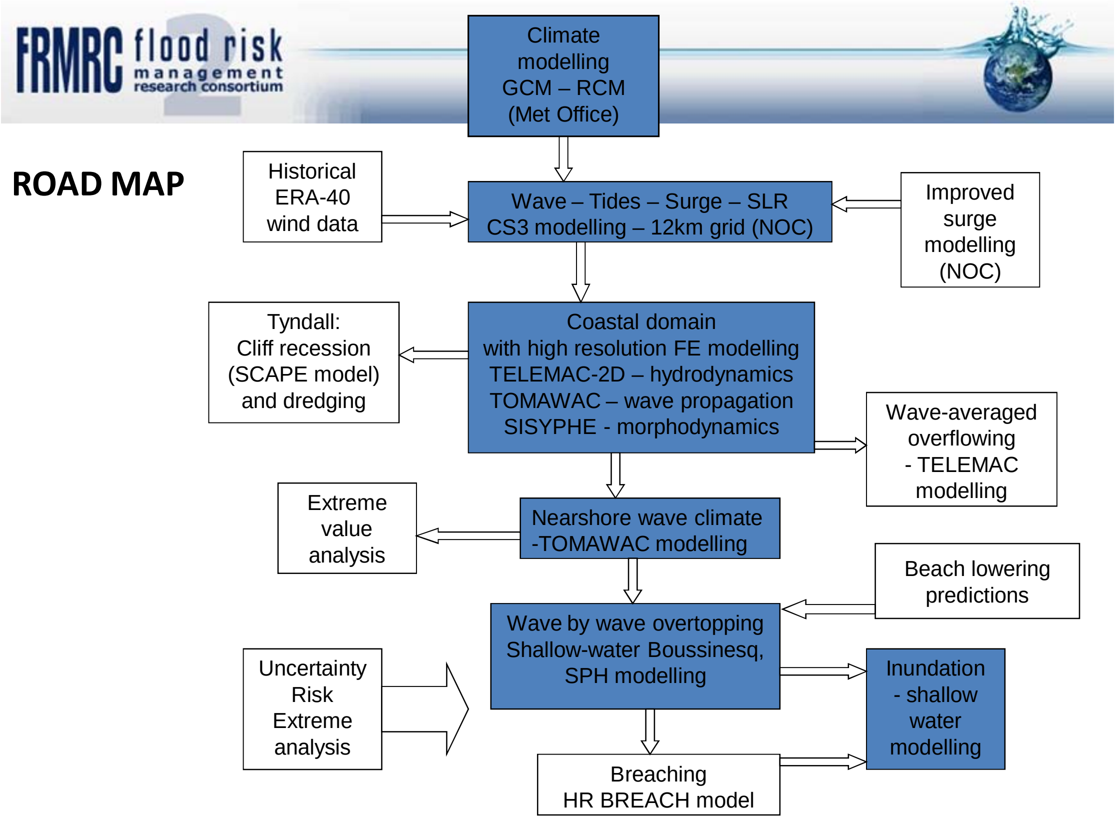
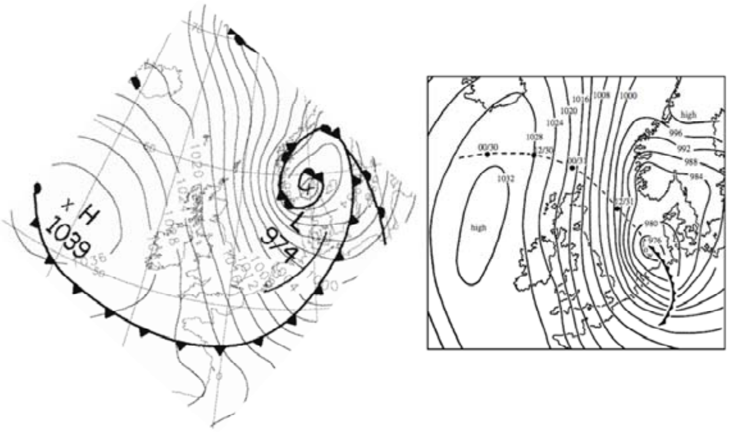


Figure 1 Road map interlinking the components of FRMRC's coastal research.
© Peter Stansby

Topics in blue boxes in Figure 1 would be covered during the workshop; the topics in white boxes are interlinked aspects of FRMRC's research. The general methodology, reference focus, data sources, and field applications for the workshop presentations would be primarily in relation to (i) the storm and subsequent inundation at Walcott on 9th November 2007 and (ii) overtopping measured at Anchorsholme, Blackpool in January 2008 by HR Wallingford for the Environment Agency, field measurements, laboratory measurements, and modelling. The aims and applied uses of this information are to (a) predict inundation accurately from offshore conditions, (b) predict statistics of overtopping and inundation with climate change and rising sea level, (c) improve operational forecasting, and (d) analyse uncertainty. In general terms, the research seeks to understand links between broad-scale offshore conditions (for example, as shown in Figure 2) and outcomes under finer-scale nearshore conditions (Figure 3).

A list of people involved in the research is provided in the acknowledgments section at the end of this report.

Walcott flood
9th Nov 2007
(from NOC)



Surface pressure analysis at 00:00 GMT, 9th Nov. 2007

Surface pressure analysis at 00:00 GMT, 1st Feb. 1953

from Horsburgh et al. (2008)

from Wolf and Flather (2005)

Figure 2 Large-scale atmospheric forcing patterns for two flood events: Walcott, 2007, and the North Sea flood event, 1953. © Horsburgh et al. (2008) and Wolf and Flather (2005)

Coastal domain

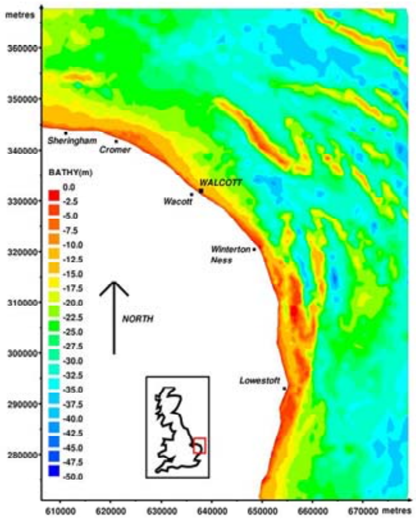


Figure 3 Finer-scale nearshore conditions. © Peter Stansby

LEARNING POINTS

1. Models are increasingly powerful and useful tools for examining the links between broad-scale offshore conditions and nearshore impacts.

2. It is essential to identify and minimise or constrain uncertainty in order to increase forecast accuracy and confidence in recommendations based on predictions.

3. Sources of uncertainty in any dynamic system depend on the model starting point, forcing, and physical rules about structure and dynamics.

4. Regional modelling of water levels is generally sufficient for predicting nearshore conditions.

5. Testing to date confirms that numerical tools can be used to model overtopping.

6. Dynamic quadtree grids are very useful in simulating flood inundation. Buildings should be represented as solid obstacles rather than using bed roughness and porosity. Local networks of road channels and ponds or fields are also important.

CHRIS WILSON, NATIONAL OCEANOGRAPHY CENTRE

Offshore wind, waves, tides and storm surges

- *Chris has been a Sea Level Modeller and Physical Oceanographer at the National Oceanography Centre, Liverpool since 2006. He worked with the Centre for Global Atmospheric Modelling at the University of Reading during 2000 and 2001, and the Department of Earth and Ocean Sciences at the University of Liverpool from 2001 to 2005. Chris has a PhD in Physical Oceanography, University of Liverpool*.

Chris' presentation provided an overview of the physical processes and spatial scales relevant to flood forecasting, as well as discussion of predictability and new modelling developments. This included an outline of the approaches used to determine offshore hydrodynamics (wind, wave, tide, and storm surge conditions) required for input into coastal models.

The aim of the research is to predict overtopping at relatively small scale, and at the level of impact on human communities and activity. To determine the processes that cause overtopping it is necessary to link large-scale weather systems to smaller-scale processes. For example, to determine the differences and similarities between broad scale weather conditions (such as shown in Figure 2 above) and how these relate to outcomes near to shore at local scale. The North Sea storm surge event of 1953 was particularly devastating. Although coastal defences have improved considerably since 1953 it would be beneficial to have improved forecasts indicating when to close storm barriers. Examples of inundation and current barriers are shown in Figure 4.

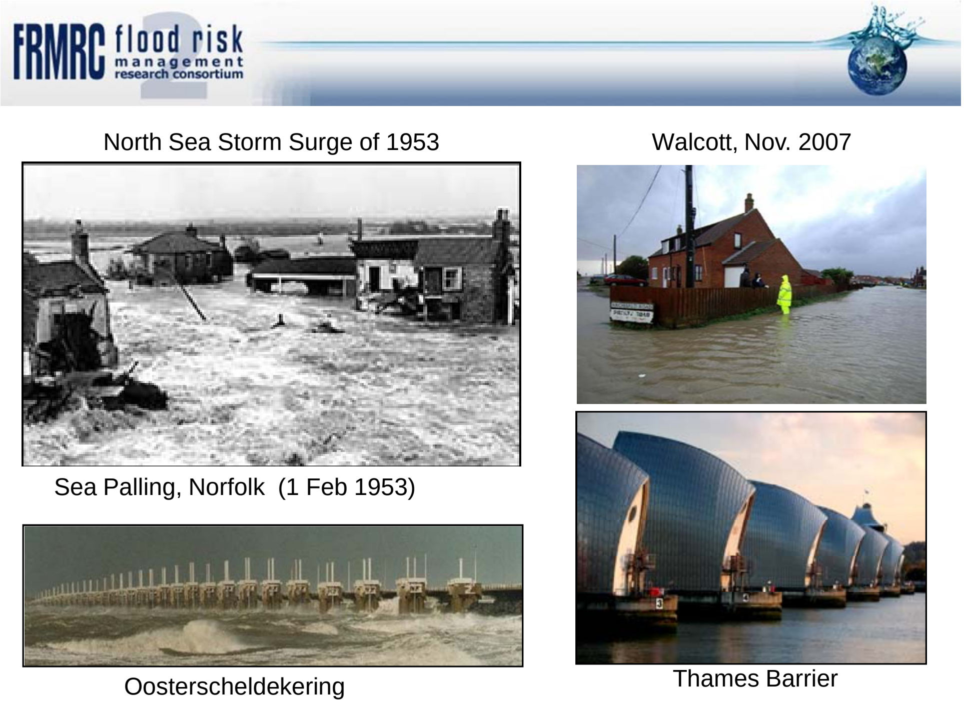


Figure 4 Examples of inundation events and current storm barriers. © Judith Wolf

The research uses nested models rather than large-scale models because they have higher resolution, providing greater detail at local scale. Relevant physical processes include tide (which is influenced by the sun, moon, and earth's rotation), atmospheric pressure, wind, surge, and waves: Figure 5. The UK Tide Gauge Network is part of the National Tidal and Sea Level Facility and its data are used to provide and improve forecasts of tide and surge. Model inputs are derived from observations and measured physical parameters. The model software uses physical equations to interlink a series of components that generate the required outputs – in this case, forecast conditions such as water level. A level of uncertainty is inherent at each stage of the modelling process. It is essential to identify and minimise uncertainty, or to at least constrain variation in factors contributing to uncertainty, in order to increase forecast accuracy and confidence in recommending actions on the basis of model predictions.

A WAM wave model and a POLCOMS tide-surge model have been utilised as inner models for Met Office mesoscale models to attempt to reduce uncertainty. The former is a spectral wave model acknowledging that wave height and period increase with wind speed, fetch and duration. The latter model has demonstrated a good fit between forecasts and surge observations, confirming that both models facilitate fine tuning for specific past flooding events. Sources of uncertainty, and hence forecast accuracy, in any dynamic system depend on model starting point, forcing, and physical rules about structure and dynamics. Traditionally, these sources of forecast uncertainty are explored with large ensembles with sets of perturbed parameters. However, as such ensembles are computationally expensive; an alternative approach is to use adjoint models to reduce total run time. The MIT gcm adjoint tide-surge model is a tool developed by the FRMRC for this purpose. The model tests input code sensitivity on a line-by-line basis to determine impacts on model output, fine tuning the modelling process to increase forecast accuracy.

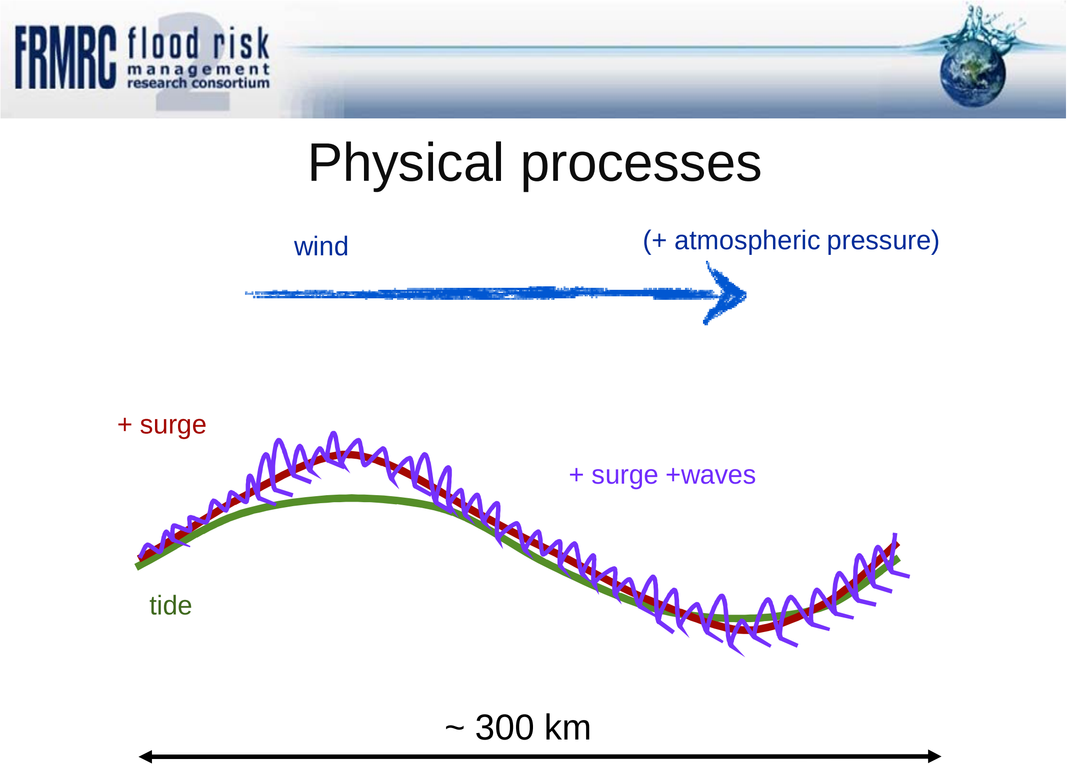


Figure 5 Physical processes relevant to flood forecasting. © Chris Wilson

DISCUSSION

Q? What level or range of reduction in uncertainty is achievable in models?

A The level or range of potential reduction in uncertainly varies across locations and events. Currently for example, we aim to reduce uncertainty from around ten centimetres to a few centimetres if possible. However, many variables are usually involved and this makes the process increasingly complex.

Q? What amount of forecast lead time that you work with?

A This can range from a few hours up to 48 hours, and occasionally information may be available up to 120 hours. The models are based on a snapshot at a point in time.

NICOLAS CHINI, UNIVERSITY OF MANCHESTER

Nearshore coastal hydrodynamics

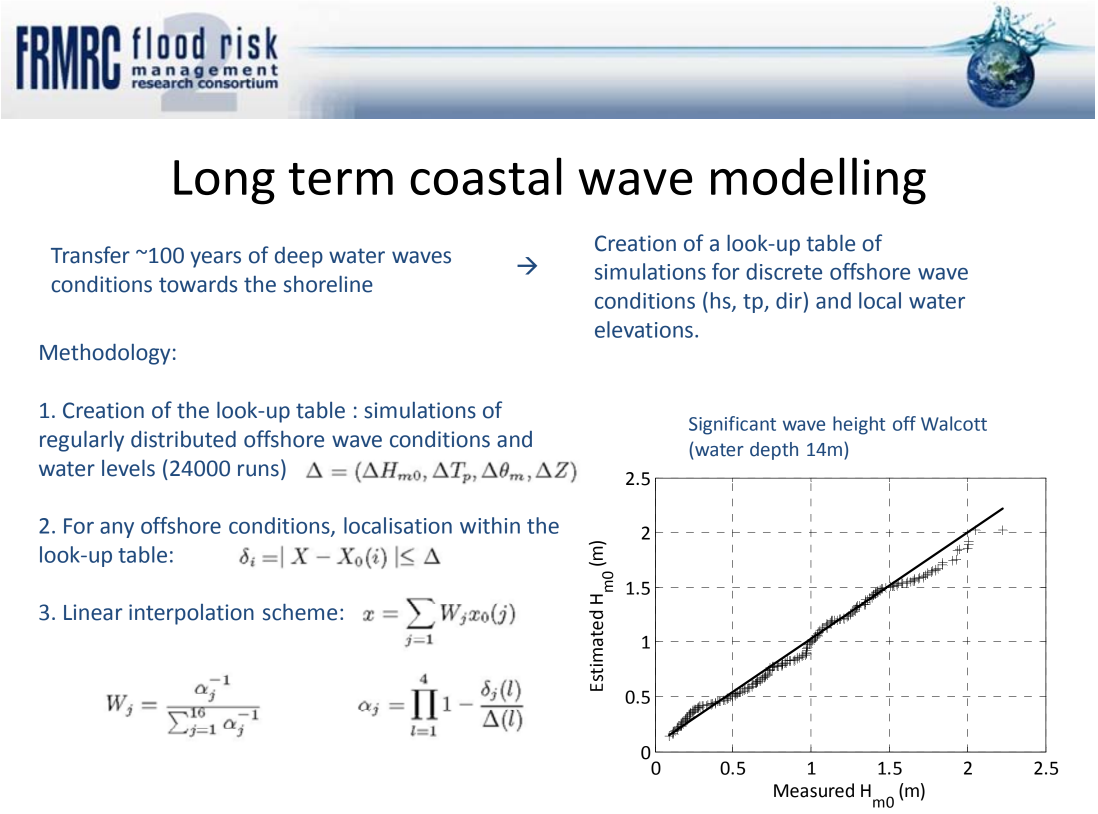
- *Nicolas is currently a Research Assistant and PhD student at the University of Manchester. After graduating in Coastal Oceanography at Brest University and ENSTA Bretagne, he worked on sandbank modelling in the Gironde estuary and developed tools for filtering tidal signal in order to perform long term simulations. These tools were then adapted to open coasts while Nicolas moved on to the University of Manchester. His other research interests include extreme values analyses and the impact of climate change on coastal processes*.

Nicolas' presentation focused on nearshore water levels and wave height modelling, including methods to estimate historical data and projections regarding sea level rise and climate change. The presentation provided an outline of work to predict nearshore wave conditions and water levels, and how this will impact coastal and beach zones.

The research is providing insights into how climate change could impact near-coastal hydrodynamics. This incorporates determining (a) how to predict nearshore conditions from offshore operational modelling systems, (b) whether sea level rise (SLR) and/or climate change (CC) will modify the occurrence of extremes, and (c) how to deal with long term simulation over approximately 100 years.

Moving from regional to coastal modelling involves developing a localisation map and local computational grid. The grid has 2877 nodes referring to distances from 2000m to 700m derived from 2002 bathymetry data (Seazone Ltd); spatial downscaling uses bilinear interpolation and temporal downscaling uses linear interpolation. Modelling coastal tide surge involved solving a depth-averaged Saint-Venant equation with TELEMAC2D (EDF R&D) for water level at Lowestoft during the November 2007 inundation event. Coastal wave modelling involved solving a wave action conservation equation with TOMAWAC. This incorporated accounting for bathymetric wave breaking, shoaling, bottom friction, bathymetric refraction, and variation in water depth due to tides and surges.

Methods used to construct the long term coastal wave model are shown in Figure 6. The model was tested via historical hindcasting using profiles from strategic surveys (EA) and offshore wave conditions from CETMEF (1979-2002) in conjunction with data for nearshore conditions at Walcott on 9 November 2007. Long term coastal wave modelling produced a scatter plot of water level and significant wave height projected over a period of 140 years (1960-2100). Further projection included the influence of sea level rise (SLR) of 2, 3.5, 4.2, 7, 10, and 20 mm per year. Extreme value analyses for nearshore conditions showed that extreme values for influence of SLR on water level increased linearly with SLR; there were no linear trends for SLR influence on nearshore waves, although extremes were increased marginally by SLR.



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Long term coastal wave modelling

Transfer ~100 years of deep water waves conditions towards the shoreline → Creation of a look-up table of simulations for discrete offshore wave conditions (hs, tp, dir) and local water elevations.

Methodology:

1. Creation of the look-up table : simulations of regularly distributed offshore wave conditions and water levels (24000 runs) $\Delta = (\Delta H_{m0}, \Delta T_p, \Delta\theta_m, \Delta Z)$

2. For any offshore conditions, localisation within the look-up table: $\delta_i = | X - X_0(i) | \leq \Delta$

3. Linear interpolation scheme: $x = \sum_{j=1} W_j x_0(j)$

$$W_j = \frac{\alpha_j^{-1}}{\sum_{j=1}^{16} \alpha_j^{-1}} \qquad \alpha_j = \prod_{l=1}^{4} 1 - \frac{\delta_j(l)}{\Delta(l)}$$

Significant wave height off Walcott (water depth 14m)

Figure 6 Methods used in long term coastal wave modelling. © Nicolas Chini

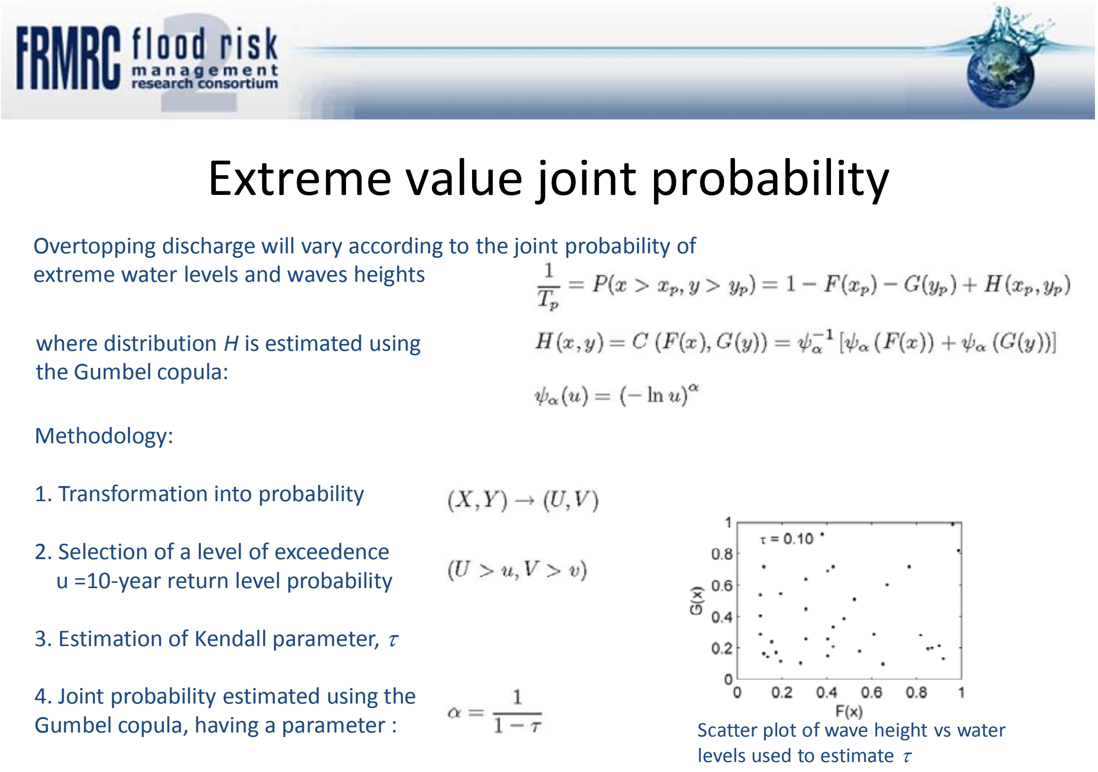
Methods used to examine extreme value joint probability, and estimate the extent of dependency between water level and wave height variables, are shown in Figure 7. With a one metre SLR in 2100 the conditions of the 2007 inundation event at Walcott become more frequent. With no SLR, the event RP is about 1:120 years. With a 3.5mm per year increase in SLR the event RP becomes 1:5 years in 2100. With a 10mm per year increase in SLR the event RP becomes less than 1:2 years in 2050.

The research has set up and validated a model to transfer wave parameters towards the shore that includes the effect of varying water depth, with a reasonable computational time, showing that regional modelling of water levels is sufficient for predicting nearshore conditions.

DISCUSSION

Q? Why did you use the particular site that you selected?

A Availability of data, which were sufficient for modelling and which should not have been affected by changes since baseline events or when parameterised.



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Extreme value joint probability

Overtopping discharge will vary according to the joint probability of extreme water levels and waves heights

$$\frac{1}{T_p} = P(x > x_p, y > y_p) = 1 - F(x_p) - G(y_p) + H(x_p, y_p)$$

where distribution *H* is estimated using the Gumbel copula:

$$H(x,y) = C\left(F(x), G(y)\right) = \psi_\alpha^{-1}\left[\psi_\alpha\left(F(x)\right) + \psi_\alpha\left(G(y)\right)\right]$$

$$\psi_\alpha(u) = (-\ln u)^\alpha$$

Methodology:

1. Transformation into probability $(X,Y) \rightarrow (U,V)$
2. Selection of a level of exceedence u =10-year return level probability $(U > u, V > v)$
3. Estimation of Kendall parameter, τ
4. Joint probability estimated using the Gumbel copula, having a parameter : $\alpha = \frac{1}{1-\tau}$

Scatter plot of wave height vs water levels used to estimate τ

Figure 7 Methods used to examine extreme value joint probability. © Nicolas Chini

MAURICE McCABE, UNIVERSITY OF MANCHESTER

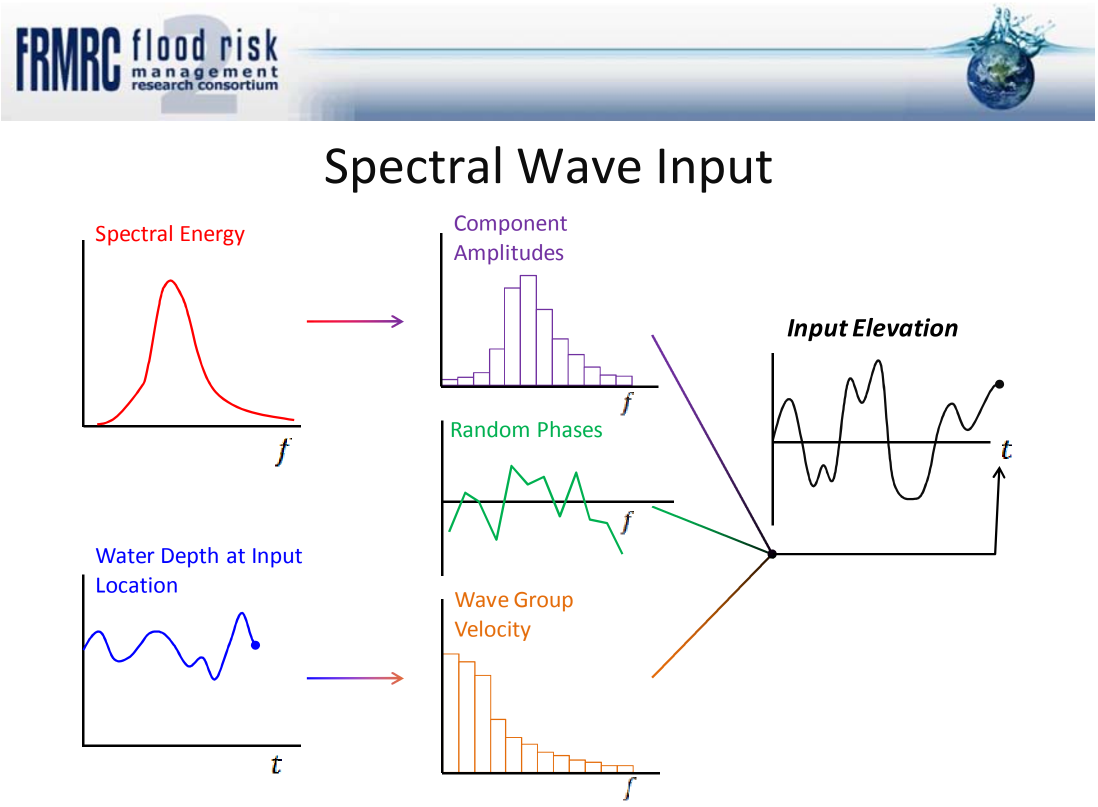
Numerical prediction of wave overtopping

- *Maurice is currently a Research Assistant at the School of Mechanical, Aerospace and Civil Engineering, University of Manchester. Maurice has been a PhD student at the University of Manchester for the last three years, researching the modelling of nearshore waves, including the runup and overtopping of coastal structures. He is now in the final stages of writing up his thesis. Maurice has previous experience at Black and Veatch doing flood and coastal defence work for the UK Environment Agency*.

Maurice’s presentation discussed the use of numerical models to predict and analyse wave overtopping, including (a) comparison of shallow water and Boussinesq (SWAB) type modelling results with experimental and field data, (b) an analysis on the effect of beach profile on overtopping rates, (c) a model of the November 2007 Walcott event, providing input for flood inundation models, and (d) some results of smoothed particle hydrodynamics (SPH) modelling.

Determining whether we can use a numerical tool to model overtopping has included a wave by wave analysis with tides and surge, examining the effect of beach profile, and EuroTop comparisons. Models have been tested with field data from the Walcott and Blackpool case studies, and also provide input for other flood inundation models. There are several options when aiming to predict wave overtopping. Physical models can be complex and expensive to construct, while empirical tools can be ambiguous because it is often difficult to achieve data consistency. However, numerical models can overcome these problems.

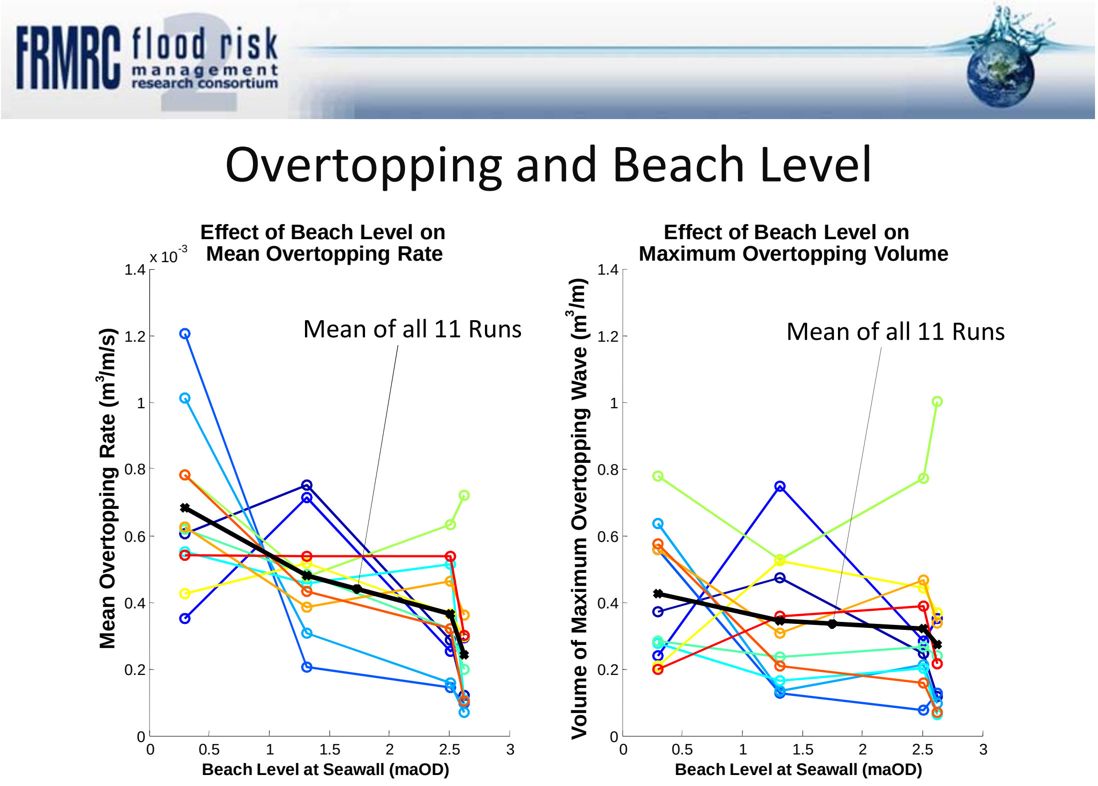
The principles of conservation of mass and conservation of momentum underlie most models. Nonlinear shallow water equations are well-suited for shallow depths but are not useful beyond these depths, while Boussinesq-type equations are appropriate at intermediate and deeper depths. Wave breaking is the trigger for the model, in terms of where breaking starts and what happens to breaking waves, and is dependent on the ratio of wave height to water depth. Wave input for the model was derived from Larsen and Dancy (1983), including energy velocity as a function of wave frequency and water depth. Spectral wave input is shown in Figure 8. Model validation to date has included solitary waves, regular waves, random waves, and wave run-up, as well as wave overtopping and field data (as the focus of this presentation).



Spectral Wave Input

Figure 8 Spectral wave input. © Maurice McCabe

Model validation for wave overtopping included data for the Anchorsholme seawall at Blackpool, field data from HR Wallingford and the Environment Agency, and tests of 1:15 scale models at HR Wallingford. Because the model had difficulty with seawalls with steps and recurve walls it was necessary to adjust by applying force at recurve walls; the model then provided a good fit with the experimental data. Beach profiles for the SWAB model were for 1991, 1996 (lowest), 2002 (highest), and 2007. Wave input involved running 11 sets of random wave phases with 200 waves per run. Results showed that wave trains differ greatly and higher beach levels are associated with less overtopping (and vice versa): Figure 9.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Overtopping and Beach Level

Figure 9 Results for overtopping and beach level. © Maurice McCabe

Output from Nicolas Chini's model was then used to test the model in relation to the storm at Walcott in November 2007. Mean rate of overtopping volume throughout the storm was 0.45 litres per second per metre, which provided good agreement with actual values even though maximum rate approached 1.0 litres per second per metre. Joint probability analysis confirmed a high level of model agreement with resident recall at Walcott. Testing to date confirms that we can use a numerical tool to model overtopping.

It is also possible to incorporate splash and spray into models of overtopping. This is often approached through smoothed particle hydrodynamics (SPH) which provides a high level of resolution but is a very complex, multi-phase, multi-scale, and nonlinear process. A promising tool for SPH analysis is *SPHysics* modelling software, which is being developed collaboratively by the University of Manchester (UK), John Hopkins University (USA), Universidade de Vigo (Spain), and University of Rome La Sapienza (Italy). Code for the software has been released as free open-sourceware, accessible at http://www.sphysics.org.

DISCUSSION

Q? Is a rule that as beach level increases there will be less inundation?

A No, this is not certain. Although it is a trend, it is not a rule in all cases.

Q? Are there joint probabilities for wave period, rather than only wave height?

A Although lower wave height over long wave periods can also have a large effect, overtopping is still primarily a function of wave height and they are highly correlated.

ALISTAIR BORTHWICK, UNIVERSITY OF OXFORD

Inshore inundation

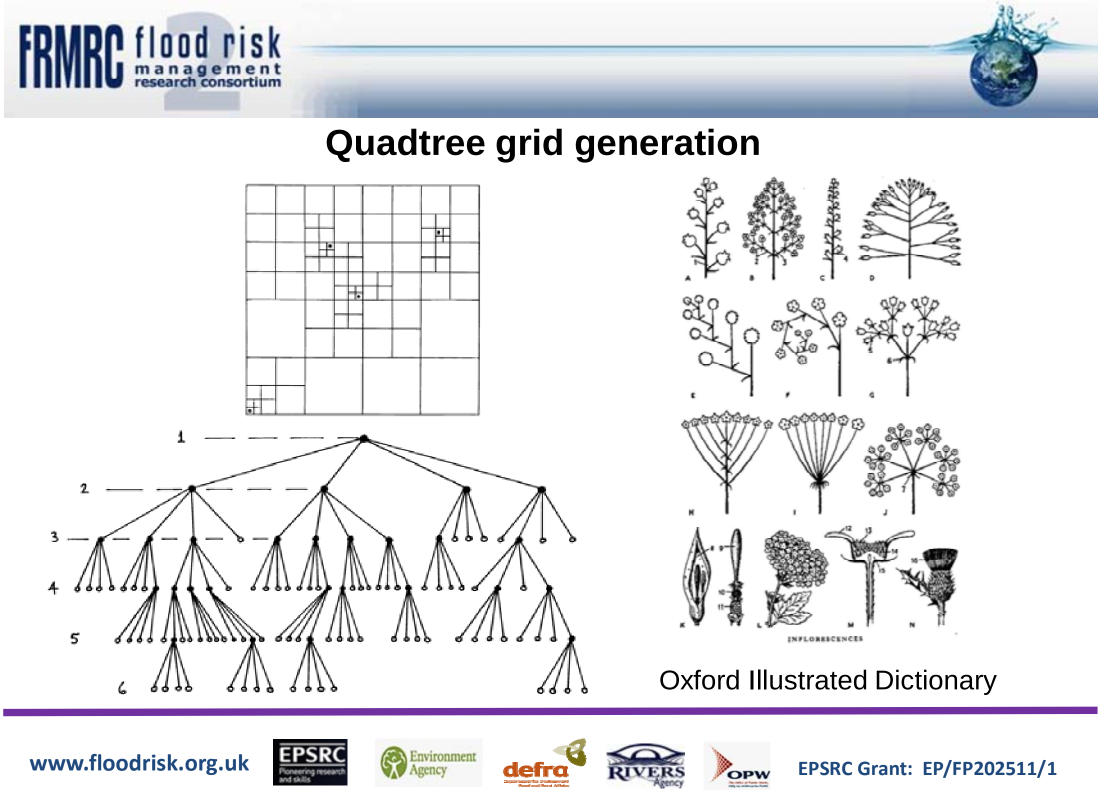
- *Alistair is currently Professor of Engineering Science at the University of Oxford. He has more than 30 years of experience as a Civil and Environmental Engineer, and is a Fellow of the Institution of Civil Engineers. Alistair has an extensive track record of research in shallow flow modelling and flood risk. He has authored up to 90 journal papers on aspects of environmental engineering*.

Alistair provided an introduction to coastal flood inundation, along with a description of dynamic quadtree grid solver of shallow water equations developed at the University of Oxford. Verification and validation results were included and simulations of coastal inundation of Walcott due to wave overtopping were discussed, demonstrating that it is better to represent man-made structures by solid obstacles rather than porosity or bed roughness. The presentation also highlighted some key implications for flood risk management.

Prior to the November 2007 inundation event at Walcott there had been infrequent but major flood disasters in Europe:

Date	Location	Deaths	Origin
1342	St Mary Magdalene, Europe	> 6,000	River
1362	Grote Mandreke, Holland	> 25,000	Storm surge
1421	St Elizabeth's Flood, Holland	2,000 to 10,000	Storm surge
1530	St Fleix's Flood, Holland	> 100,000	Storm surge
1634	Buchardi Flood, Holland	8,000 to 15,000	Storm surge
1953	North Sea Flood, UK and Holland	2,400	Storm surge

Flood flows generally present three difficulties for models: wet-dry fronts, steep fronted trans-critical flows (flow discontinuity), and complicated terrain. The adaptive quadtree grid generator developed at the University of Oxford is a hierarchical code that facilitates grid generation by spatial domain decomposition. It is robust, computationally efficient, and fully automated; it is also easy to adapt dynamically and very useful for flood simulation. Quadtree grid generation, as illustrated in Figure 10, is a structured process.



Quadtree grid generation

Oxford Illustrated Dictionary

www.floodrisk.org.uk

EPSRC Grant: EP/FP202511/1

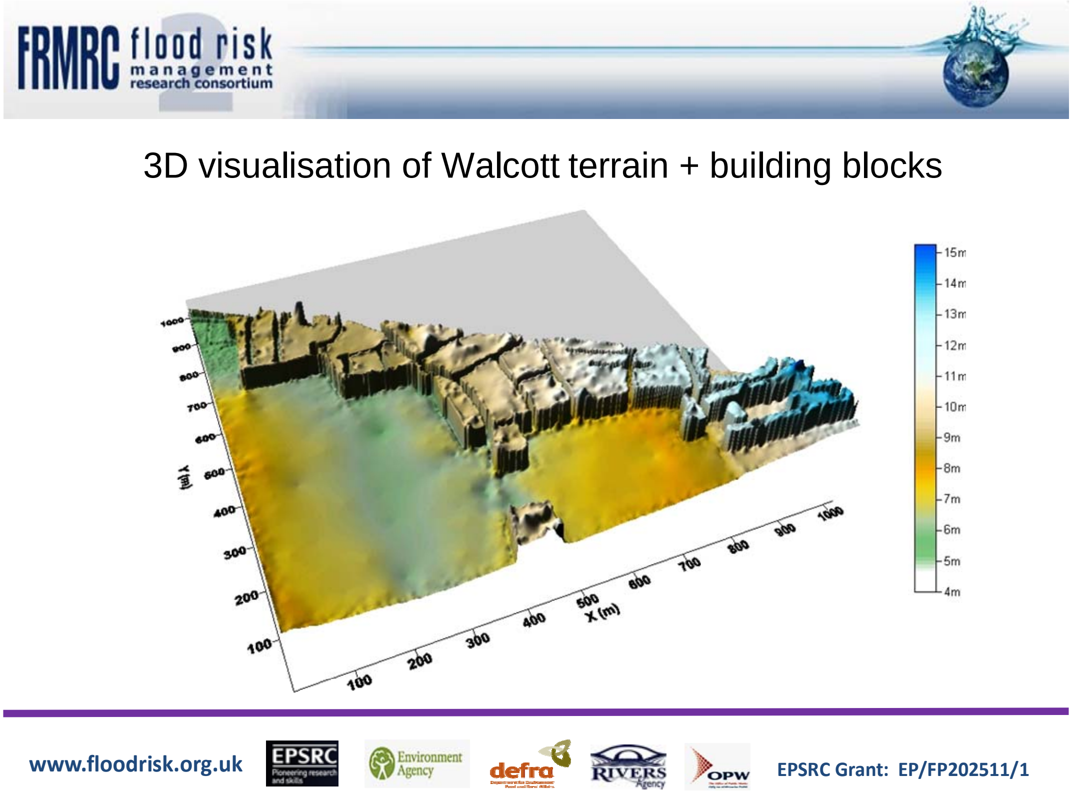
Figure 10 Quadtree grid generation. © Alistair Borthwick

The shallow water-sediment solver incorporates a series of governing equations:

- Mass conservation for water-sediment mixture
- Momentum conservation for water-sediment mixture
- Suspended sediment transport equation
- Bed load transport formula
- Bed material conservation equation

These are solved using a shock-capturing finite volume scheme. There is extensive evidence that this approach works well in complicated domains, including tests with experimental simulations. For example, shallow lakes and lagoons (Borthwick, Cruz León, & Józsa, 2001), dyke breaks (Liang, Borthwick, & Stelling, 2004), dam-break wave interaction with three humps (Liang & Borthwick, 2009 as well as Kawahara & Umetsu, 1986), and urban flood risk (Liang, Du, Hall, & Borthwick, 2008).

A series of photographs of Walcott on 14 January 2010 (see Yan, 2010) showed not only that the area is very flat and has many motor homes and caravans, but also that ditches connect to the sea wall. A 3-dimensional surface visualisation of the terrain and building blocks at Walcott is shown in Figure 11. Four numerical simulations of the Walcott inundation were conducted – results are shown on slides 34 to 42 of Alistair's presentation.



3D visualisation of Walcott terrain + building blocks

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EPSRC Grant: EP/FP202511/1

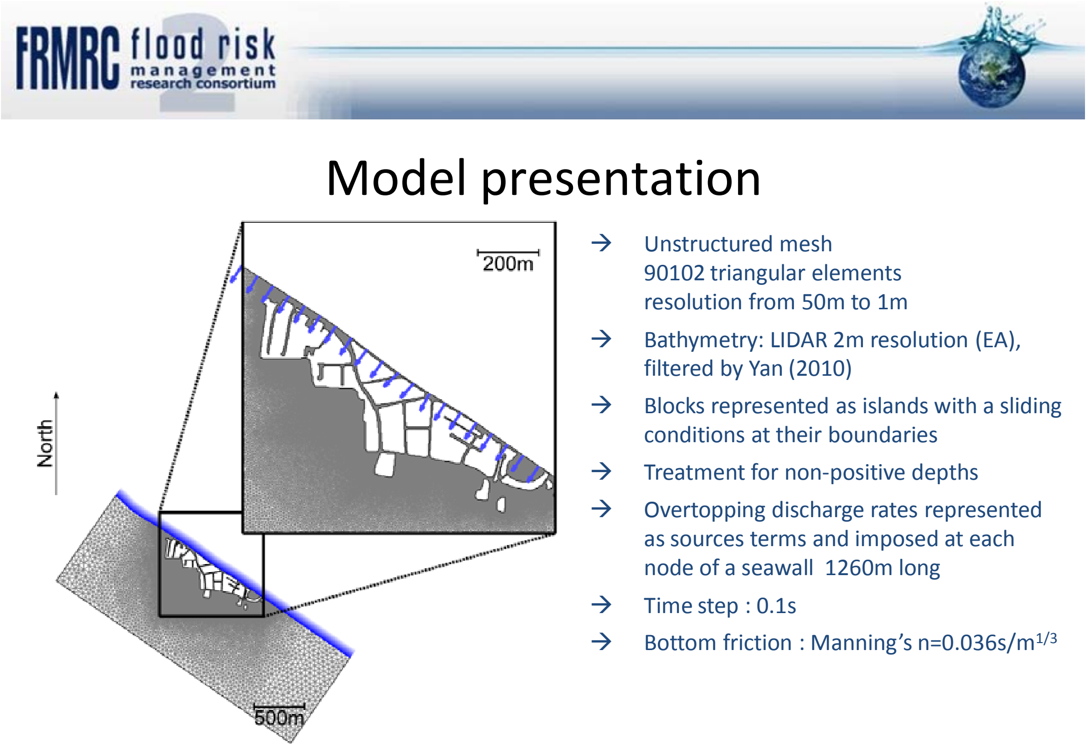
Figure 11 3-D visualisation of Walcott terrain and building blocks. © Alistair Borthwick

Overall, the research confirms that dynamic quadtree grids are useful in simulating flood inundation. It is recommended that buildings are represented as solid obstacles rather than using bed roughness or porosity. In general, bed roughness and porosity are not the best way of representing urban areas. Simulation of the Walcott inundation demonstrates the importance of the hydraulic network of road channels and ponds or fields. There is a need for similar flood evolution maps for constant and time-dependent wave overtopping events in Walcott.

NICOLAS CHINI, UNIVERSITY OF MANCHESTER

Coastal inundation at Walcott using TELEMAC system

Following the main presentations outlined above, Nicolas Chini provided additional analysis of the 2007 inundation event at Walcott using the TELEMAC system. This research considered (a) how to transform overtopping discharge into flooding maps, (b) the appropriate tools for this, and (c) how to provide guidelines for coastal flood mapping due to wave overtopping. Model presentation is shown in Figure 12.



Model presentation

- → Unstructured mesh
  90102 triangular elements
  resolution from 50m to 1m
- → Bathymetry: LIDAR 2m resolution (EA), filtered by Yan (2010)
- → Blocks represented as islands with a sliding conditions at their boundaries
- → Treatment for non-positive depths
- → Overtopping discharge rates represented as sources terms and imposed at each node of a seawall 1260m long
- → Time step : 0.1s
- → Bottom friction : Manning's n=0.036s/m$^{1/3}$

Figure 12 Model presentation using the TELEMAC system. © Nicolas Chini

Wave by wave input and hourly averaged input both showed a high level of overtopping discharge between 2 and 3 hours. Model predictions for the Walcott event were tested for accuracy by comparing them with residents' recall. This aspect of the research demonstrates that a model based on FE method can be set up to transfer overtopping discharge into flooding maps. Inputs are represented by source terms in order to add the right volume into the domain. Model outputs showed similar flood extent for both constant and time-dependent wave overtopping at Walcott. The model also includes computational grid modification to include ditches.

GROUP DISCUSSION

Q? Are the same principles and theory applicable for inundation maps?

A Yes, they are the same and equally applicable.

Q? Is it appropriate to compare simulations between the adaptive grid approach and the TELEMAC system?

A It is generally not appropriate. Benchmarking is the primary test and also more informative than running the approaches against each other. They can be run against each other when there is a benchmark, in order to indicate the relative benefits and shortcomings of each model and how they are coded. In addition there is a need for high quality field data for comparisons.

Q? How time consuming is the process of running these models of overtopping?

A Relatively quick. Running time for simulation of one storm is generally one to two hours.

Q? What was the reasoning for the conclusion that steps and recurve walls create problems for overtopping models?

A Steps and recurve walls are more like roughness than a change in horizontal momentum. The model must adjust and also be calibrated for this, based on sound physics. The model calculates a reflection force.

Q? Has there been any work with inundation modules regarding the time and/or manner in which waters dissipate or flow back?

A Not to date, although it would be interesting to examine post-flood behaviour. This would necessitate further fine tuning of the model as well as accounting for evaporation and porosity.

Additional comments: The work regarding joint probability is very impressive; this is a useful and informative analysis that should be conducted more often. Quantification is also very important, particularly knowing the extent of overtopping in order to manage it. It is also important to have lead time to evacuate people and protect property when specified sets of adverse weather conditions arise. There is a need to reduce levels of uncertainty, especially in terms of advance prediction time. Sources of sea-level forecast uncertainty are due to uncertainty in weather forecasts, or in the parameterisation of processes such as bottom drag which affect large-scale offshore conditions, eg the tide. These practical applications are important for those working as practitioners in the field.

CONCLUDING REMARKS

Tools for examining overtopping and inundation are largely available and functioning, and are improving all the time. This is a direct reflection of the efforts that have gone into these models. It has been a large investment in time that is now providing returns. It would be productive to extend the research to examine other types of flooding, such as longer waves, different forms of waves, and interactions with wind, which can vary considerably across geographic regions.

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