Simulating tidal and storm surge hydraulics with a simple 2D inertia based model, in the Humber Estuary, U.K.

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Key Points

1. CEASAR-Lisflood shown to accurately reproduce tidal elevations
2. Storm surge peak tides and flood extents both modelled close to observed
3. Model used data available publically in real/near time

Abstract

The hydraulic modelling of tidal estuarine environments has been largely limited to complex 3D models that are computationally expensive. This makes them unsuitable for applications which make use of live data to make real/near time forecasts, such as the modelling of storm surge propagation and associated flood inundation risks. To address this requirement for a computationally efficient method a reduced complexity, depth-integrated 2D storage cell model (Lisflood-FP) has been applied to the Humber Estuary, UK. The capability of Lisflood-FP to reproduce the tidal heights of the Humber Estuary has been shown by comparing modelled and observed tidal stage heights over a period of a week. The feasibility of using the Lisflood-FP model to forecast flood inundation risk from a storm surge is demonstrated by reproducing the major storm surge that struck the UK East Coast and Humber Estuary on 5 December 2013. Results show that even for this 2013 extreme event the model is capable of reproducing the hydraulics and tidal levels of the estuary. Using present day flood defences and observed flooding extents, the modelled flood inundation areas produced by the model were compared, showing agreement in most areas and illustrating the model's potential as a now-casting early warning system when driven by publically available data, and in near real-time. The Lisflood-FP model used was incorporated into the CAESAR-Lisflood GUI, with the calibration and verification of the estuarine hydraulics reported herein being a key step in creating an estuary evolution model, capable of operating in the decadal to century timescales that are presently underrepresented in estuarine predictive capability, and ultimately developing a model to predict the evolution of flood risk over the longer term.

Key Words

Numerical Modelling; Estuaries; Tides; Storm Surge; Flooding; Prediction

1. Introduction

Estuaries are complex environmental systems, situated at the confluence of freshwater fluvial systems and saline, open-sea environments. There is a long history of modelling processes within estuaries and coastal zones (Brush and Harris, 2010; Baird and Mehta, 2012) and a key component of estuarine models is simulating the complex flow interactions and resultant flow patterns. To date, the hydraulics of estuaries have been successfully modelled with a range of 2 and 3 dimensional numerical schemes (Murray, 2007) with earlier methods making extensive use of 2D models (e.g. Cheng *et al.*, 1993; Lin and Falconer, 1995). However, since the late 1990s, with the increase in cheap computational power, these methods have been superseded by more complex 3D models.

Recent examples include the 3D Delft3D model built by WL|Delft Hydraulics (as described in Lesser *et al.*, 2004), which has proven a popular choice for the modelling of detailed hydrodynamics (e.g. Harcourt-Baldwin and Diedericks, 2006; van Maren, 2007; Hu *et al.*, 2009; Van der Wegen and Roelvink, 2012). To simulate flow patterns these 2 and 3D hydraulic models solve the full shallow water equations. However, the numerical complexity of solving the shallow water equations can make these methods computationally expensive thus restricting their application to short time scales and/or coarse spatial resolutions (Li *et al.*, 2005; Warner *et al.*, 2005; Harcourt-Baldwin and Diedericks, 2006; Vaz *et al.*, 2009). Ultimately, this restricts their application, sometimes making them impractical for simulating the longer time scales often required to operationally examine system evolution (Williams, 2012). The computational overhead also hinders their capability to generate rapid simulations that could be used for real/near time flood protection applications, and for ensemble predictions for detailed uncertainty analysis and thus more robust future predictions.

The scope of modelling of fluvial hydraulics and flood risk has similarly been restricted by the complexity of 2/3D full hydraulic models, but in this field an emerging body of simplified quasi 2D flow models - often termed 'storage cell' models - has developed. Models such as Lisflood-FP have been successfully applied and tested to simulate hydraulics in shallow water environments where there is a strongly unidirectional flow (Bates and De Roo, 2000; Bates *et al.*, 2010; Neal *et al.*, 2011; Stephens *et al.*, 2012; Coulthard *et al.*, 2013; Wong *et al.*, 2014). Additionally, Lisflood-FP has been shown to be especially adept at dealing with situations where there is rapid wetting and drying making them ideal for dealing with flood inundation (Bates *et al.*, 2010). Most recently, Lisflood-FP was successfully used to simulate coastal flooding from storm surges in the Bay of Bengal (Lewis *et al.*, 2013). The reduction in numerical and computational complexity of models such as Lisflood-FP has been shown to not significantly reduce the predictive capability of modelling flood inundations, with other factors, such as the spatial resolution of the Digital Elevation Model (DEM) used, often proving more influential than the physical complexity of the model itself (Neal *et al.*, 2012).

Adapting and applying simple hydraulic models such as Lisflood-FP to estuarine environments would be a logical step to enable rapid simulations of large areas, long time periods and for ensemble runs. In this paper, we take the Lisflood-FP model and apply it to the Humber Estuary, UK, and demonstrate the viability of using the Lisflood-FP model as a real/near time flood risk tool by simulating a major storm surge event in the Humber Estuary which occurred on 5 December 2013. Simulation results are then compared to tidal stage data from recorders located along the estuary, and flood inundation areas from the surge derived from aerial photography taken approximately 12 hours after the event.

2. Methods

2.1 The Lisflood-FP Flow Model and CAESAR-Lisflood

The version of Lisflood-FP presented in this paper is embedded as the hydraulic element of the CAESAR-Lisflood (C-L) model (Coulthard *et al.*, 2013). This model is an integration of the Lisflood-FP code of Bates *et al.* (2010) and the CAESAR cellular automata (CA) Landscape Evolution Model (LEM) of Van de Wiel *et al.* (2007), which links the hydraulics of the former with the erosion and deposition components of the latter. In this paper the geomorphic component (erosion and deposition) of C-L is not explored. The Lisflood-FP model integrated in C-L (Bates and De Roo, 2010) discretises the flood plain into grid cells and calculates the flux of water across the two Cartesian boundaries of these cells (e.g. the X and Y directions) via Equation 1:

$$Q = \frac{q - gh_{flow}\Delta t \dfrac{\Delta(h+z)}{\Delta x}}{(1 + gh_{flow}\Delta t n^2 |q| / h_{flow}^{10/3})} \Delta x$$

(1)

where Q is the flow between cells, q is the flux between the cells in the previous iteration, g is the acceleration due to gravity, n is the Manning's n roughness coefficient, h is the water depth, z is the elevation of the bed, h_{flow} is the maximum depth of flow between the cells, Δx is the grid cell resolution and t is time. Having established the flow, the water depth of the cell is calculated by Equation 2:

$$\frac{\Delta h^{i,j}}{\Delta t} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x^2}$$

(2)

where i and j are the cell coordinates. Finally, Equation 3 is used to formulate the model timestep, controlled by the shallow water Courant-Friedrichs-Lewy (CFL) condition:

$$\Delta t_{\max} = \alpha \frac{\Delta x}{\sqrt{gh}}$$

(3)

where α is a coefficient typically set between 0.3 and 0.7, which enhances the model's robustness (see notes on Model Instability below).

Lisflood-FP has been extensively tested and compared to other hydraulic models in benchmarking studies (Neal *et al.*, 2012), that have demonstrated that in fluvial settings the model was capable of simulating flow depths and velocities within ten percent of a comparative range of industry full shallow water codes. However, there are limitations with the Lisflood-FP code as it is not a full 2D solution. For example, high degrees of flow deflection around a meander bend are not well simulated, and as shown by Bates *et al.* (2010) and Neal *et al.* (2011) the model should not be applied in sub-critical flow conditions. These limitations, however, need not preclude it from estuarine applications.

Model Instability

The Lisflood-FP model was derived from equations commonly used by 1D model models, and uses the CFL function (Equation 3) to determine a timestep with which the model can operate with stability. Model stability and time stepping within Lisflood-FP is discussed in detail in Bates *et al.* (2010) and Almeida *et al.* (2012) but in summary, Equation 3 shows how this timestep is closely related to flow depth and the spatial resolution used for simulations. Due to the increased complexity of 2D simulations, and the use of a friction function, it was found that the required timestep was often lower than that produced by the CFL function resulting in instability (Bates et al., 2010). To compensate for this, Bates et al. (2010) introduced the α function into Equation 3 to further reduce the timestep and avoid the model instability, and in our simulations the algorithm was shown to be stable within the range of spatial resolutions and scenarios run, including a full tidal cycle.

2.2 The Humber Estuary: Context and previous research

The Humber Estuary (Figure 1) is a large tidal-dominated estuary on the East coast of England and is of international importance because of its natural habitats (parts of the estuary has Site of Special Scientific Interest (SSSI) status), and is economically important containing major UK ports at Hull, Grimsby, Immingham and Goole. The combined Humber-Ouse system has a mean spring tidal range of 5.7 m and tidal length that extends 120 km from the mouth (Mitchell *et al.*, 1998).

On the evening of 5 December 2013 a large storm hit the East Coast of the UK, tracking from the north, southwards along the East Coast, resulting in the largest storm surge in the Humber Estuary since 1953 (Wragg, 2014). In the city of Hull, a tidal barrier, built following the 1953 storm surge event, came close to overtopping with levels 0.62 m greater than the previous highest recorded tide in 1990 (Wragg, 2014). However, flooding did occur within the city centre to the west of the barrier as the tidal surge overtopped the defences at Albert Dock. In total, 115 businesses and 149 residential properties were affected by the flood waters in the city of Hull alone (Wragg, 2014). Raynor and Chatterton (2014) described the flooding around the estuary, stating that in total 40 km of defences were overtopped flooding an area of 7,000 ha, including the sea defences at Cleethorpes, the gates of Grimsby's Royal Dock and extensive flooding at Immingham Port.

Previous research that has modelled the tidal hydraulics in the Humber Estuary includes using a 2D finite difference model on a 500 m grid, limited to the outer estuary bathymetry, in order to assess suspended sediment fluxes (Falconer and Owen, 1990). Their model showed a visual fit between modelled and recorded data for a single site near Immingham and only over a single, average tidal cycle. The ULTIMATE QUICKEST scheme was subsequently applied to the Humber by Lin and Falconer (1995). This was incorporated into a 2D depth-integrated model where modelled and recorded stage heights were compared at three sites in the outer estuary, showing a good visual fit over a single spring tide and a single mid-tide. Lin and Falconer (1997), and later Wu *et al.*, (1998), subsequently applied a 3D model to the Humber Estuary, again showing a good visual fit between flow velocities and stage heights over a single tidal cycle, using a 500 m resolution grid of the outer section of the estuary.

Whilst successfully applied, the models above were only deployed over short time scales, on limited sections of the estuary and at a grid cell resolution no greater than 500 m. They were not applied to the full estuary, have not accounted for the fluvial inputs and would require significant adaption in order to model inundation of the flood plain. However, owing to the computational resources available at the time of these studies, it is more than reasonable to assume that if the studies were performed with current resources then each of these conditions could be significantly improved upon. A more recent example of hydraulic modelling of the Humber Estuary has used Delft3D, but only modelled a single spring-neap cycle, with the aim of studying residual flows and sediment dispersion only (EstProc, 2003) - again this was applied to only a section of the estuary and at a grid cell resolution of 500 m.

2.3 Study Data

2.3.1 Digital Elevation Model

The elevation data for the study was provided from three sources. Bathymetric data of the estuary bed was provided as point samples, collected in 2010, by the Association of British Ports (ABP) and the point elevations were interpolated using Topo-to-Raster within ArcMap 10.1 to a contiguous grid of 50 m resolution. Uncertainty associated with the interpolation could be assessed by excluding a set of 100 randomly selected points from the interpolation and comparing their point elevation to the elevation of the interpolated cell containing the point. From this separate analysis the RMSE of the 50 m interpolated grid was 0.57 m. The bathymetric elevations provided by ABP were collected using chart datum and required a correction to be applied to bring it into line with the Above Ordnance Datum (AOD) used by other data sources. As the difference between chart datum and AOD is not consistent along the estuary's length an interpolated grid of values was used to apply the correction, based on the corrections provided by ABP for each of the tidal stage recorders (locations can be seen in Figure 1).

Outside of the tidal channels, Light Detection and Ranging (LiDAR) elevations were provided at a 2 m cell resolution for the intertidal zone and surrounding flood plain by the UK Environment Agency (EA). The Digital Terrain Model (DTM) data were used, showing the 'bare earth' elevations. The LiDAR elevation data were processed to have a RMSE of less than 0.15 m (personal correspondence with the EA's Geomatics team by email, 8 April 2014).

The final source of elevation data was the Ordnance Survey's OS Terrain 50 product, available from Digimap (EDINA, 2014). The topography is based upon photogrammetry and is provided at a 50 m grid cell resolution. The error associated with OS Terrain 50 product is not known, but comparisons with differentially corrected GPS performed on the higher resolution OS Terrain 5 product showed a RMSE less than 2.5 m (Ordnance Survey, 2013). The OS Terrain 50 data was only used where no alternative elevation data were available and is unlikely to fall in an area that will undergo modelling of water flows.

A composite 50 m DEM was produced by converting each of the elevation data sources into a 50 m point cloud, where overlapping points were excluded so each area was represented by only a single point elevation. The selection of the points was such so as to show priority first to bathymetry (where data were collected), second to LiDAR elevations, and finally, where data for neither of the other sources were available, topographic data from the OS Terrain 50 dataset were used. The point clouds were interpolated together using the Topo-to-Raster tool in ArcMap 10.1 with hydrological enforce enabled. Topo-to-Raster incorporates the ANUDEM algorithm that was developed for interpolated topographic surfaces and has been used previously for merging LiDAR and bathymetric data in intertidal zones (Gesch and Wilson, 2002).

The final component of the DEM was incorporated after the interpolation. This was a flood defence asset layer provided by the EA as a Polyline layer containing the elevations of the flood defences along the Humber Estuary. The elevation value of each grid cell that was intersected by the Polyline layer had its elevation increased to the maximum value of the Polyline within that grid cell.

2.3.2 Tidal Stage Data

The tidal stage data for the Humber Estuary used in this study were provided by ABP, from a set of 10 stage recorders distributed within the estuary, with stage heights sampled at 5 minute intervals. Figure 1 shows the locations of the tidal stage recorders spanning 80 km of estuary.

The C-L model was driven using tidal stage heights from the Spurn Point recorder and applying them to the grid cells on the furthest eastern point of the DEM (shown in Figure 1), that essentially raised and lowered the water depth along this boundary. Elevations between each 5 minute sampling frequency were linearly interpolated to the model timestep. The uncertainty associated with the recording of tidal stage heights and the interpolation is not known.

2.3.3. Fluvial Inputs

The tidal influence of the Humber Estuary extends for tens of kilometres inland with the tidal Ouse extending 60 km inland from Trent Falls to near York (Mitchell *et al.*, 1998). As no discharge data were available for the points of fluvial inputs in the model, stage heights from recorders close to the fluvial inputs (Goole on the River Ouse and Flixborough on the River Trent: Figure 1) were used to raise and lower the water depth in the grid cell(s) at the river input points - as per the tidal input at the mouth. This method is especially useful for real/near time simulations where live discharge data are unavailable but stage heights are. As with the tidal stage heights in Section 2.3.2, the uncertainty with the fluvial inputs used here is not known.

2.4 Calibration

An iterative manual calibration of the model was performed using a 500 m resolution DEM, produced by a cubic resample of the 50 m resolution DEM in ArcMap 10.1. The coarser grid cell resolution allowed for very rapid computation times on a multi-core desktop PC (< 1,200 seconds to simulate 1 year; Intel Core i7-3920k @ 3.20 GHz). The calibration was performed using tidal stage height data collected for the whole of 2010. The model utilised a spatially uniformed value of Manning's n roughness coefficient, and calibration was performed by altering this value and visually comparing the simulated tidal stage heights with those recorded for various periods in the year. It was found that the model favoured very low values of Manning's n (< 0.02).

To account for some of the uncertainty in the selection Manning's n, three different values were chosen to perform the test. The upper value was 0.019, with a mid-value of 0.015 and a lower limit of 0.010. The upper limit represents a physically realistic value of roughness based on Chow (1959) and Acrement and Schneider (1989), with 0.019 being within the range for a freshly dredged channel. The mid-value is the value suggested by McCutcheon *et al.* (1990) for a wide, deep channelled estuaries, with a high level of sediment and transport, and high turbidity (as per the Humber Estuary). These values are low - and McCutcheon *et al.* (1990) and King and Wolanski (1996) explain this is due to the influence of very high sediment concentrations held in a turbulent area just above the estuary bed as a basal liquid mud layer, which acts to significantly reduce the friction between the flow and the bed. The lowest value corresponds with the lowest suggested value for use in the Lisflood-FP model by Bates *et al.* (2013). It is worth noting that for Lisflood-FP, Manning's n can be used to calibrate/adjust the model, and does not have to be physically based.

2.5 Verification and Validation Methods

The performance of the C-L model in simulating the tidal flow in the Humber Estuary was assessed using five statistical measures. Firstly, common measures of goodness of fit were calculated in the form of R^2, shown in Equation 4, and the root-mean-squared-error (RMSE), as in Equation 5:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(m_i - o_i)^2}{\sum_{i=1}^{N}(m_i - \overline{m}_i)^2}$$

(4)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(o_i - m_i)^2}{n}}$$

(5)

where, o_i is the observed tidal stage height at timestep i, m_i the corresponding simulated stage height and $\overline{m}_i$ the mean of the simulated stage heights. Comparisons were made at each 5 minute timestep. The peak stage heights were compared using the RMSE between the modelled and recorded peak stage heights at a daily timestep.

The relative size of the simulated error compared to the recorded stage heights was further assessed using a *Perror* score, calculated using Equation 6:

$$Perror = 100.\frac{\hat{m} - \hat{o}}{\hat{o}}$$

(6)

where, $\hat{m}$ denotes the maximum modelled value within the time period examined, and $\hat{o}$ denotes the maximum observed value within the time period examined. In this case the peak values were obtained on a daily basis. Unlike the RMSE, *Perror* provides information on the direction of the error. It is important to note that neither of these error scores provides information on errors with regards to the timing of the peak tides.

The final measure used is the *skill* value as developed by Wilmott (1981), calculated using Equation 7:

$$skill = 1 - \frac{\sum_{i=1}^{N} \left| m_i - o_i \right|^2}{\sum_{i=1}^{N} \left(\left| m_i - \overline{o}_i \right| + \left| o_i - \overline{o}_i \right| \right)^2}$$

(7)

where $\overline{o}_i$ is the mean of the recorded stage heights. A *skill* value of 1 would show a perfect fit between the recorded and modelled stage heights, and a value of 0 represents no skill.

The *skill* score of Wilmott (1981) has been commonly used to assess the performance of models to predict stage heights in estuaries (Li *et al.*, 2005; Warner *et al.*, 2005; Vaz *et al.*, 2009). In these previous cases the measure has been used to assess the performance of complex 3D models simulating estuarine conditions that present a greater modelling challenge than the Humber Estuary.

The performance of the model was assessed by comparison between the recorded and simulated stage heights over a sample week (Week 48) that was selected as it provided a near complete record across the stage recorders. The performance of the model for the simulation of the 5 December 2013 storm surge event was conducted by comparing recorded and simulated heights for 5 December 2013. As data from the Spurn Point, Goole and Flixborough tidal stage recorders were used to drive the model these were excluded from the analysis.

2.6 Flood Inundation

To assess the capability of C-L to simulate the spatial extent of flooding, flooded areas were digitised from aerial oblique photography collected by the EA on the morning of 6 December 2013 (examples in Figure 2). It should be noted that as the images were captured over 12 hours after the peak of the flooding they are known to underestimate the extent of inundation as flood water drained by the time the aerial photography was captured.

For example, the aerial photographs show little visible signs of flooding within well drained urban and industrial areas, despite known extensive flooding in Hull and Immingham Port, as well as flooding in Grimsby and Cleethorpes (Raynor and Chatterton, 2014; Wragg 2014). The lowland areas of the Humber Estuary also have a wide network of drains and ditches that are effective at removing flood waters. Many of these surface drainage features (ditches, channels) are small and to depict them here would require a DEM of far finer resolution than the 50 m resolution DEM used. Additionally, the relatively dry antecedent conditions to the storm surge had also left the surrounding flood plain with capacity to absorb some of the flood water via infiltration.

The extents of the observed inundation were digitised over a Digital Surface Model (DSM) of 2 m resolution LiDAR of the area in ArcMap 10.1, using field boundaries as a reference. These were compared visually against modelled inundations collected at midnight on 5 December 2013 simulation time - after the peak of the flood, when the inundation had ceased to spread. As here C-L does not represent the drainage or removal of water into the ground, the modelled flood remained in place and this represents the peak inundation from the flooding.

3. Results

3.1 Calibration

The calibration of the model was performed using data for the full year of 2010. Figure 3 shows stage heights for Week 48 of the simulation, using a Manning's n roughness coefficient value of 0.015. The 1:1 comparisons are shown on the right hand side. The charts show the stage recorders in order from Sunk Island close to the mouth of the estuary, to Blacktoft Jetty along the River Ouse.

Visually, the simulated and recorded stage heights show a close fit throughout the estuary, especially up to and including Albert Dock (40 km from the mouth). Beyond the Humber Bridge recorder the performances begin to deteriorate. There are also visual hysteresis effects in the results for the Blacktoft Jetty recorder.

The results for the statistical measures suggest a good fit (Table 1). The model showed the best performance using a Manning's n roughness coefficient of 0.015 for all the measures and every recorder. At 0.015 the mean RMSE was 0.22 m across the stage recorders, and the mean RMSE of the peak stage heights was 0.11 m which was generally higher than the recorded indicated by the positive *Perror* score of 3.17 %. Mean R^2 and *skill* scores were close to 1 for each of the values but greatest for 0.015.

Overall, from each measure there is a loss of performance as the distance from the mouth increases, becoming noticeably greater for the recorder along the River Ouse (Blacktoft Jetty). The difference in RMSE between relatively small variations of Manning's n roughness coefficient (no greater than 0.005) exceeds the vertical RMSE of the 2 m LiDAR data, but not the RMSE in the interpolated Bathymetric data.

3.2 Storm surge stage performance

Tidal stage data for the period 1-6 December 2013 (including the 5 December 2013 storm surge event), provided by ABP, was used to drive and analyse the C-L simulations of the storm surge event. The model was run using tidal stage heights recorded from the Spurn Point stage recorder, and fluvial inputs were represented using stage heights recorded from the Goole and Flixborough stage recorders (Figure 1). The simulation was run for each of the Manning's n roughness coefficient value - 0.019, 0.015 and 0.010.

The performance of C-L to recreate the storm surge as it passed through the Humber Estuary was analysed using the statistical measures detailed in Section 2.5. For the stage recorders that captured a full record of the surge peak the peak stage heights were compared. Although the stage recorders used were the same as those used for the calibration of the model, due to the extreme nature of the event on 5 December 2013 the ability of the recorders to fully capture the event was impaired, with several recorders topping out (e.g. Figure 4: Immingham, Blacktoft Jetty). Other recorders were not operating during this period, or reported erroneous data, and therefore could not be used.

Figure 4 shows the tidal heights from the available stage recorders for 5 December 2013, using a Manning's n roughness coefficient of 0.015, and Table 2 shows the corresponding statistical scores for each recorder. The modelled data is able to reproduce the peak stage heights that were not recorded when the recorders topped out. For example, the peak stage height modelled at Immingham was 5.33 m, above the maximum value recorded at the same site during the 1953 event (4.52 m), even after accounting for the mean RMSE in the peak of 0.15 m. The actual peak measured at Immingham Port was 5.31 m (Raynor and Chatterton, 2014).

As per calibration the model showed the best results using the Manning's n roughness coefficient value of 0.015, and that there was a decrease on performance away from the estuary mouth. The model shows a similar level of performance to the calibration period, but the error scores are inferior in each measure. Although the model still clearly performs better using a Manning's n roughness coefficient value of 0.015, the model does show better performance using 0.010 under some metrics – using 0.010 produces better mean R^2 and *skill* scores.

3.3 Flood Inundation Reproduction

The ability of C-L to simulate the spatial extent of flooding was performed by visual comparison between aerial photography collected post-surge, and the simulated inundations from the simulations using each of the Manning's n roughness coefficients, taken as a mini-ensemble. Figures 5 to 7 show the flood inundation areas as digitised from the aerial photography and the model simulated inundation areas. The Possible, Likely and Very Likely Flooding categories are hypothetical, reflecting how a true ensemble forecast might present the flood risk – here, Possible Flooding indicates flooding predicted by only a single ensemble member, Likely Flooding where two ensemble members agree, and Very Likely Flooding when all the ensemble members agree. Operationally, such a forecast system would contain a greater number of ensemble members and the risk categories as physically based entities.

There is a visual agreement between the two flood inundations but with notable exceptions. The representation of flooding in urban or industrial areas based on the aerial photography is very poor, with the modelled inundations being in agreement with observations of flooding in Hull city centre (Wragg, 2014), and occurrences at Immingham Port and Grimsby (Raynor and Chatterton, 2014). Where the flood inundation areas overlap, the model predicts greater extents of flooding using Manning's n roughness coefficient of 0.010 and 0.015, but generally less when using 0.019. Crucially however, when the simulated outputs are taken as an ensemble, the model predicts flooding in the overwhelming majority of areas where flooding was observed.

4. Discussion

This is the first time a storage cell hydrodynamic model such as C-L has been applied in an estuarine context and it performed well predicting tidal heights in the Humber Estuary. Furthermore, the model was used to simulate the 5 December 2013 storm surge event, both recreating the tidal extremes within the estuary but also predicting the extent of flood inundation of the surrounding flood plain. This represents an important step as to date estuarine hydrodynamic models have not linked the channel and inter-tidal zone to areas outside of this domain. The model is fast, with the processing time using a multi-core desktop PC (Intel Core i7-3920k @ 3.20 GHz) at 50 m grid cell resolution averaging 2,558 seconds for a 24 hour simulation - requiring less than 1,500 seconds to simulate a full tidal cycle. Importantly, this speed enables it to be used for real-time ensemble-based prediction.

The calibration of the model for the period of 2010 showed that the RMSE between modelled and recorded tidal heights to be < 5 % of the tidal range (3.3 % using Manning's n roughness coefficient of 0.015. This puts the model's performance well within the < 20 % of tidal range bound suggested as 'good' by Brown *et al.* (2011) for a 3D model of an estuary, and the 15 % 0f spring tidal range guideline defined by the Foundation for Water Research (1993). The absolute peak RMSE for the 50 m resolution grid, Manning's n roughness coefficient of 0.015, was just 0.11 m, which is within the bounds of the vertical error of the LiDAR data alone – the same was also true for the storm surge simulation where the absolute peak RMSE was 0.15 m. The Foundation for Water Research (1993) guidelines suggest that a hydrodynamic model should be able to predict stage heights to within 0.1 m at the mouth of an estuary, and within 0.3 m at the head, and C-L has been shown to be able to comply with this standard for the calibration period - although the model does not quite meet the standards for modelling the stage heights at the Blacktoft Jetty recorder.

Comparison between this model operating in the Humber and other hydrodynamic models in different estuaries are difficult. The Humber Estuary could be described as being a relatively low complexity estuarine environment owing to the high degree of mixing. However, the C-L model for the Humber Estuary has achieved performances that are in-line with those achieved by more complex 3D models, albeit often applied in more complex estuarine environments. For example, an application of the

DELFT3D model to the Tomales Bay, USA, showed a RMSE of 0.09 m, at a single stage data recorder over 3 simulated days (Harcourt-Baldwin and Diederick, 2006). Vaz *et al.* (2009) applied the Mohid 3D hydrodynamic model to a Portuguese estuary, showing a *skill* (Equation 7) of 0.93 near the mouth, and 0.87 for a point further inland. This is similar to Warner *et al.* (2005), where a 3D model of the Hudson River estuary showed *skill* of 0.95 over 32 km away from the tidal input, and 0.85 around 110 km inland. The *skill* scores are not as high throughout the estuary as those from a 3D model based on the Regional Ocean Modelling System (ROMS) when applied to the Chesapeake Bay Estuary (Li *et al.*, 2005) for two years of hindcasts, where the *skill* remained high throughout at 0.99, reducing to just 0.98 at the furthest point inland. The analysis by Li *et al.* (2005) also included a calculation of the RMSE between modelled and observed tidal heights, which was 0.05 m close to the tidal input and the furthest point inland, although the relative percentage increased further inland. The of C-L in the Humber Estuary produced similar *skill* values, where the skill remained above 0.99 until 40 km inland, where it begins to fall to 0.96 at the furthest point inland, 67 km away at Blacktoft Jetty. Although it is not possible to say that C-L performs as well as these examples, due to the varying nature of the estuarine environments modelled, it is possible to say that C-L performs as well at modelling the Humber Estuary as these examples perform at modelling their respective study estuaries. Interestingly, all of the examples, including C-L, demonstrated a loss of performance as the distance away from the tidal input increased (although this was marginal in Li *et al.* (2005)). There are two likely explanations for this drop in performance within the C-L model.

Firstly, there is uncertainty in the unconventional datum correction applied to the bathymetric data (described in Section 2.3.1), which is not consistent across the estuary – for example, the datum correction at Spurn Point is 3.9 m, yet is 1.4 m at Goole. There is potential for error in the interpolation of the datum correction used from this point onward and this corresponds with the loss of performance in the model. If the datum correction is below what is required then gradients in the DEM's representation of the bathymetry will be steeper and result in a slowing of flow inland. The influence of DEM error on hydraulic modelling was investigated by Falcao *et al.* (2013), showing that tidal asymmetry can become more pronounced if elevations are overestimated upstream, which results in a phase delay.

Secondly, a cause for the loss of performance after the Albert Dock recorder may be the influence of the fluvial inputs and boundary conditions related to their location. There are no direct measurements of the fluvial inputs of the Trent and Ouse close to the Humber Estuary. The use of stage data to represent the fluvial inputs to the estuary was a necessity due to a lack of suitable live data at these points, but these are not ideal as the flow will not behave in the same way as a true pressure-driven fluvial input. Although the fluvial inputs into the Humber Estuary are small relative to the volume of the estuary, these inputs have been shown to be significant to certain aspects of tidal hydraulics, such as tidal wave damping/surge propagation (e.g. Cai *et al.*, 2014). A possible improvement would be to extend the extent of the model domain to beyond the reach of tidal influence, and to a point where live discharge data is available - although this will come with a loss of efficiency to the model.

The evaluation of the model's performance in predicting the inundation of flood waters is problematic due to the lack of timely data to determine the true extents of the flooding. It was fortunate, and through quick reactions of the EA, that oblique aerial photography of the estuary was captured as soon as possible after the event and this provided the best possible data to assess the performance of the model –

albeit acknowledging the limitations of this dataset as highlighted in Section 2.6. Our use of a mini-ensemble composed of the outputs of the three simulations (utilising Manning's n roughness coefficient values of 0.019, 0.015 and 0.01) is representative of a more comprehensive ensemble approach that could be employed operationally, accounting for a wider range of uncertainties. Here, the computational efficiency of this type of model allows the rapid use of ensembles. As stated previously, for the vast majority of areas where flood inundation was observed by the aerial photography the model simulated flooding within the mini-ensemble – this would mean in an operational context each area of observed flooding would have received a flood risk warning in advance of the flooding based on the simulation results.

Discrepancies between the observed flooding extents and the simulated extents is largely due to the recession of flood waters prior to the capture of aerial photographs. The nature of storm surge flooding is such that flood water inundates and retreats rapidly, with the peak flooding remaining only for a matter of minutes to tens of minutes. In areas of good drainage, especially urban and industrial areas, the flood water is effectively removed and no evidence of inundation was visible from the aerial photographs, taken hours after the event, in these areas.

The simulations did not account for elevation uncertainty in the DEM used or vertical error in the recorded stage heights. Even the relatively low vertical RMSE of 0.15 m in the LiDAR data could make the difference in the simulation overtopping in an area or not. The Humber Estuary is a dynamic system and bathymetric changes can occur rapidly. The bathymetric data used in the study was collected in 2010 and it is likely that the bathymetry in 2013 will be different in some areas (it is also likely to have change during the event itself).

There are ways in which the model's representation of flood inundation can be further improved. Further increasing the spatial resolution of the DEM would allow more detail to be represented, including small variations and local weaknesses in the estuary's flood defences. By using a fine enough resolution some of the local drainage network could also be represented. By using a relatively coarse resolution (50 m), it is necessary to use the DTM processed LiDAR to build the DEM, which shows the 'bare earth' elevations, and this creates an artificially smooth DEM that is largely free of obstacles (buildings, roads, ditches, walls etc) which would have stopped or slowed the spread of flood water. Increasing the resolution could allow for some areas to be represented using DSM LiDAR which would improve the representation of flood inundation extents, especially in urban and industrial areas. The use of a global value of Manning's n roughness coefficient will also have influenced the spread of flood water in the model, as it is likely that the roughness of the floodplain would be significantly greater than the very low values used in the estuary – using a separate value for the flood plain would likely yield a better representation of the flood extents.

Whilst C-L is fast, this is at the expense of process representation and C-L model as it currently exists, does not include representations of inertia, turbulence, Coriolis, salinity, water temperatures and wind processes. Therefore, its application to more complex estuarine environments may not be appropriate without further enhancement. The Humber Estuary is a comparatively simple estuary, tidally dominated with low Froude numbers, which suits the approach applied herein. The study has also not made any analysis of flow velocities, modelled nor recorded, and this would be required before investigation into detailed morphological processes can be performed using C-L.

5. Conclusions

This study has tested the feasibility of using a reduced complexity storage cell model to simulate the tidal heights and flood inundation extents of a 1 in 200 year storm surge event in the Humber Estuary.

In the calibration of the C-L model to the Humber Estuary, the hydraulics were tested for the first time in a tidal-dominated estuarine environment. Peak tidal heights were shown to have a low RMSE (0.11 m), slightly overestimating the peak tidal heights, but within the bounds of the uncertainty inherent in the generation of the elevation data used. The model showed a decrease in performance as the distance from the mouth increased. The model was shown to perform well using stage heights as a proxy for fluvial inputs, which is important as these are publically available in real/near time.

The effectiveness of C-L has also been shown in the simulation of the 5 December 2013 storm surge event in the Humber Estuary. The peak RMSE for the storm surge was greater than for the calibration period, at 0.15 m, although with limited data with which to determine this. This error is within the bounds of uncertainty inherent with the LiDAR elevation data alone. There was a close visual overlap between observed and simulated flood inundation areas, with the model predicting flooding in the areas where flooding was observed. The model predicted flooding in areas for which there were reports of flooding but no evidence from the aerial photography in large part due to effective drainage in the time-lad associated with the acquisition of the imagery.

This study has shown the feasibility of using Lisflood-FP for the modelling of tides within the Humber Estuary, and its ability to reproduce the flood inundation extents of a rare, extreme storm surge event. The ability to represent both the flows in the channel of the estuary and inundation in the surrounding flood plain is a particularly advantage of this method. The good performance of this reduced complexity tidal model implies that for similar tidal and estuarine conditions there may not be the need to apply more complex 3D simulation approaches. This demonstrates the potential for models like C-L and Lisflood-FP to be used as real/near time forecasting tools, using publically available data, to predict tidal surge events and flooding with an ensemble-based method. Looking forward, the Lisflood-FP code used for this study was embedded within the framework of C-L, which has the functionality to model sediment transport and morphological evolution as well (and a long, successful history of such in fluvial environments). The application of such a CA to explore geomorphic evolution in an estuarine environment would be novel and the logical next stage of this work.

Acknowledgements

The CAESAR-Lisflood model can be downloaded from www.coulthard.org.uk. The data used in this study is available, on request, from the Environment Agency and the Association of British Ports, and was provided to this study on a non-commercial license. This work was conducted as part of the Dynamic Humber Project (DHP), part of the Centre of Adaptive Science and Sustainability (CASS) at the University of Hull, and funded by a grant from the Higher Education Innovation Fund (HEIF). The Authors thank the Editor and the Reviewers for their constructive and useful comments that contributed to improving with paper.

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Figure Headings

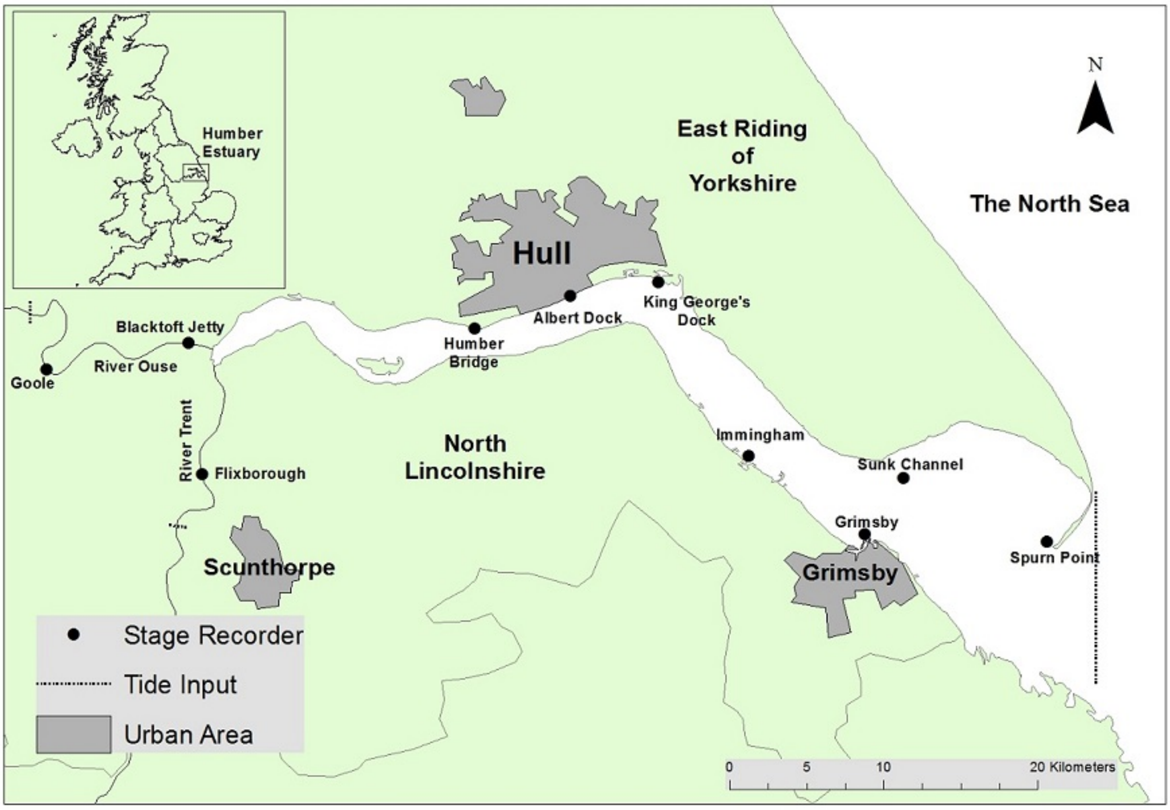

Figure 1 - Map showing the Humber Estuary, location of the stage recorders and the tidal boundaries used for the simulations.

Figure 2 - A selection of 'oblique' aerial photographs captured by the Environment Agency on 6 December 2013 showing flood extents of the storm surge the previous evening. The images show, clockwise from top-right, flooded farmland opposite Goole on the River Ouse, flooding west of South Ferriby (showing extensive damage to Reed's Island), flooding near to Skeffling on the north bank of the Humber, and the breach at Spurn Point.

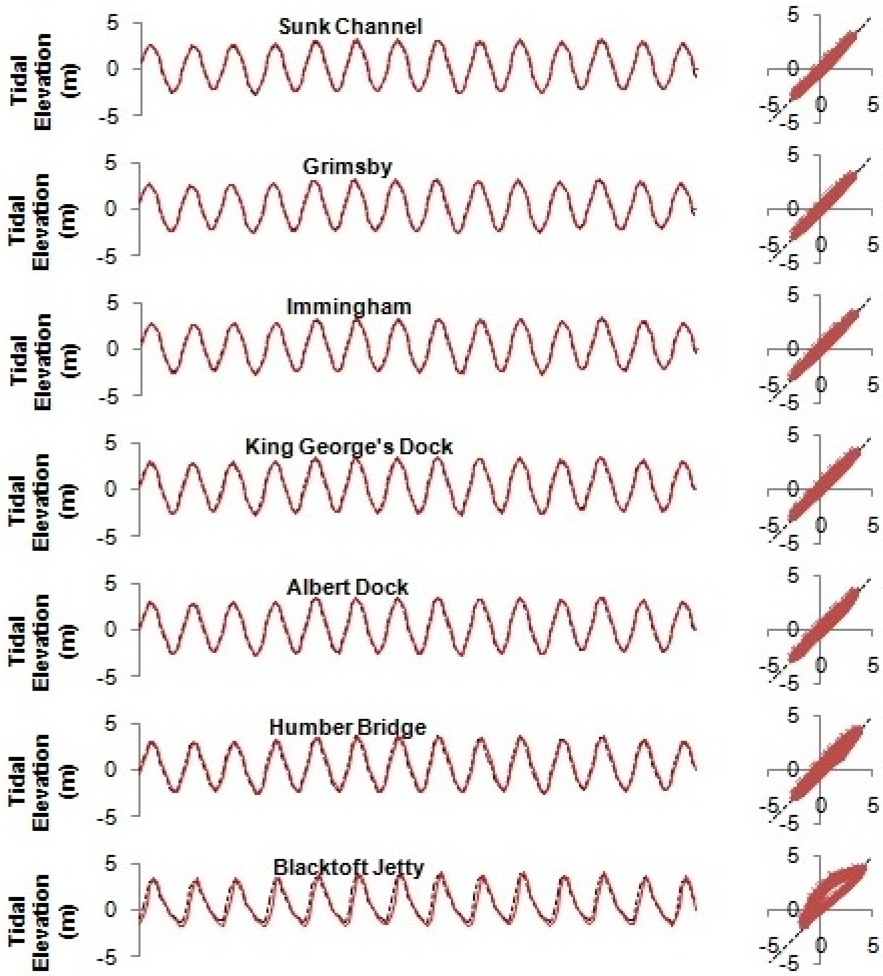

Figure 3 - Charts comparing the observed (dashed black line) and the simulated (solid red/grey line) tidal stage heights at stage recorders across the Humber Estuary, for Week 48 of the calibration period, 2010. The simulation was performed using CAESAR-Lisflood with a Manning's n roughness coefficient of 0.015. The charts on the left show tidal stage heights (as metres Above Ordnance Datum) over time, and the charts in the right show direct comparison between of modelled tidal elevations over recorded tidal elevations – the dashed black line shows the 1:1 line for perfect correlation.

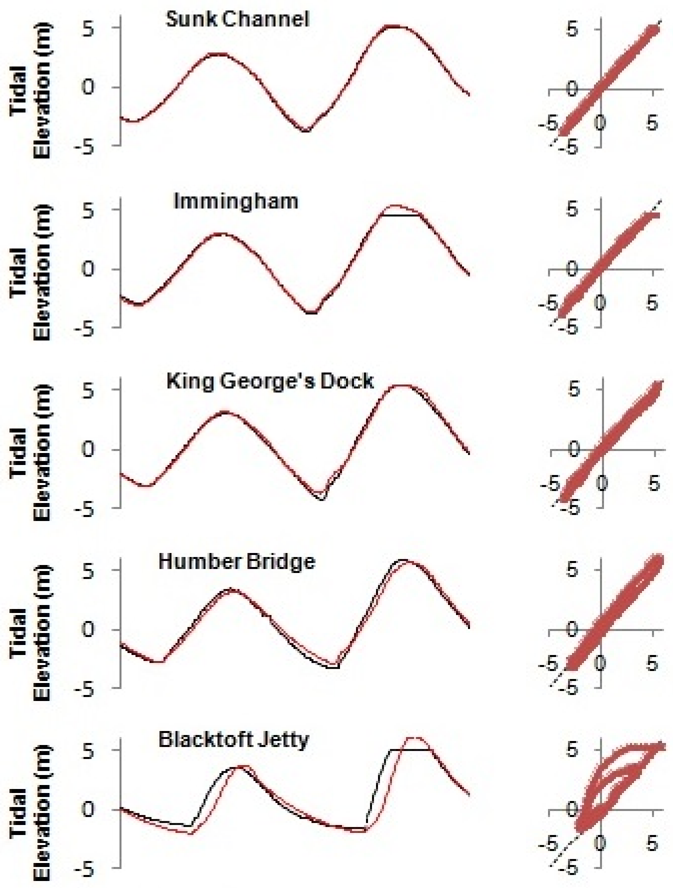

Figure 4 - Charts comparing the observed (dashed black line) and the simulated (solid red/grey line) tidal stage heights at stage recorders across the Humber Estuary, for 5 December 2013. The simulation was performed using CAESAR-Lisflood with a Manning's n roughness coefficient of 0.015. The charts on the left show tidal stage heights (as metres Above Ordnance Datum) over time, and the charts in the right show direct comparison between of modelled tidal elevations over recorded tidal elevations – the dashed black line shows the 1:1 line for perfect correlation.

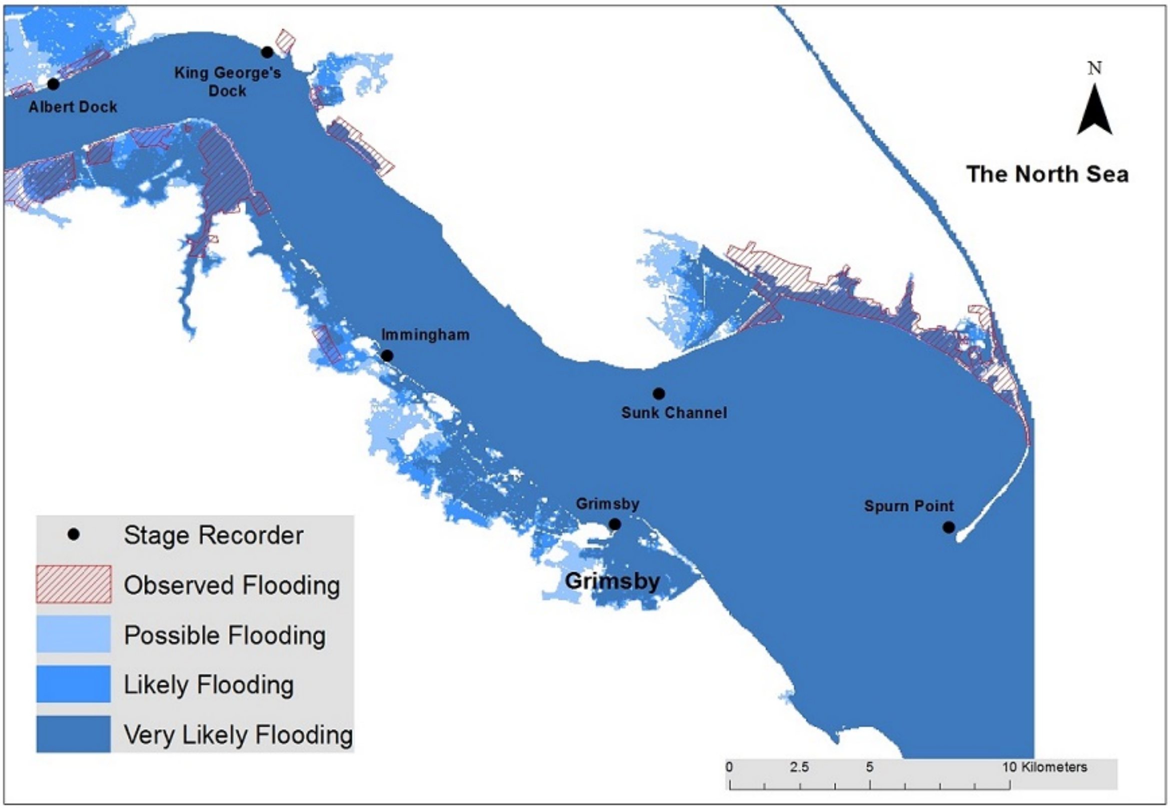

Figure 5 – Map showing the flood extents of the 5 December 2013 storm surge in the Humber Estuary for the outer section.

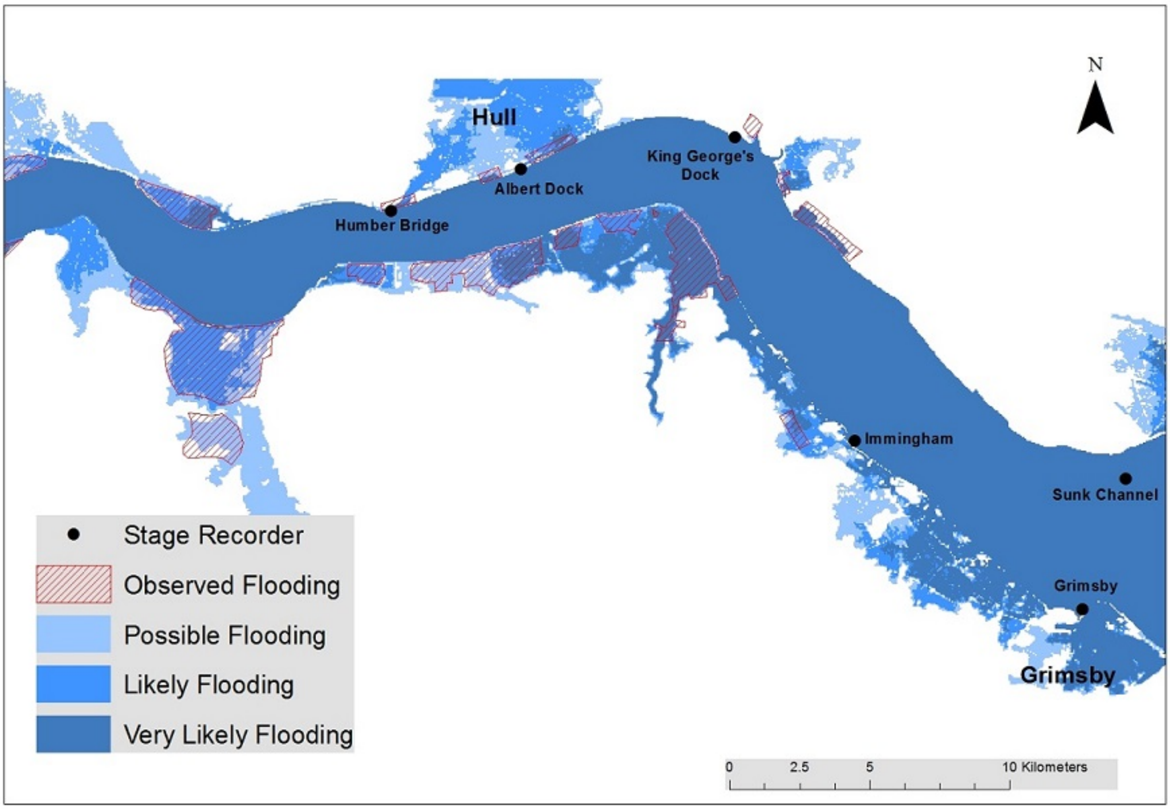

Figure 6 – Map showing the flood extents of the 5 December 2013 storm surge in the Humber Estuary for the middle section.

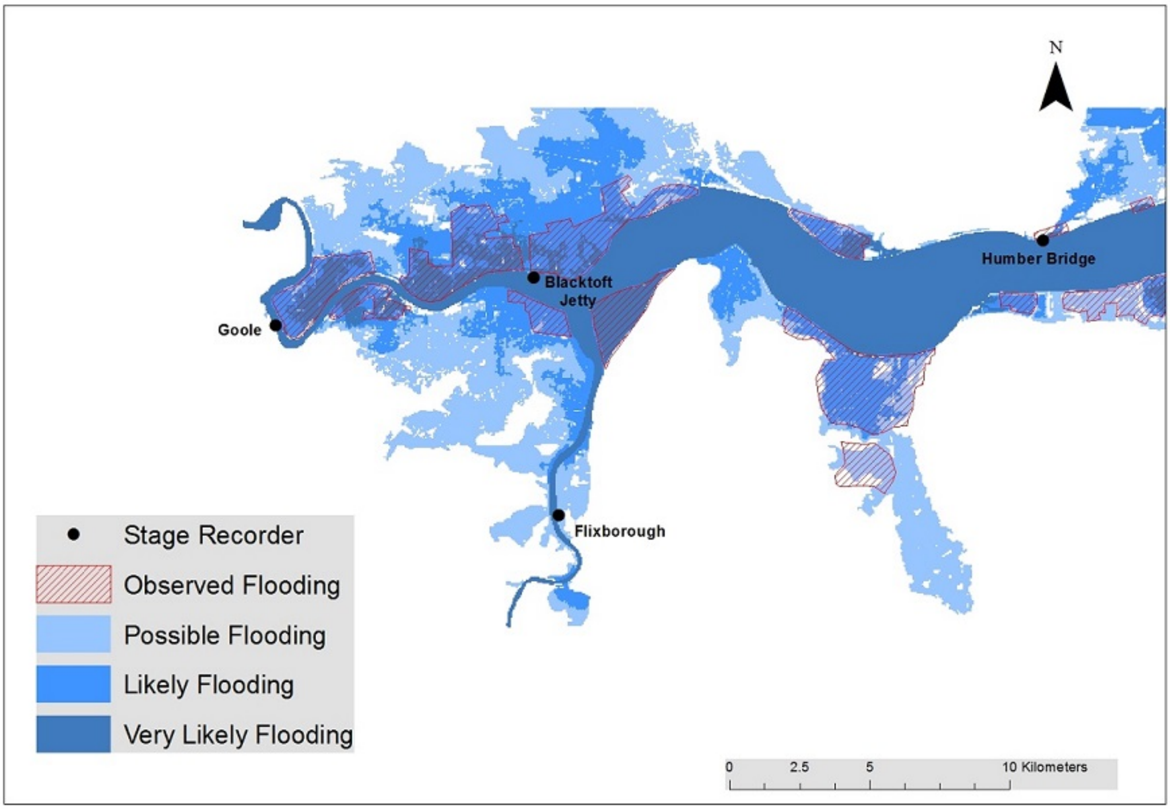

Figure 7 – Map showing the flood extents of the 5 December 2013 storm surge in the Humber Estuary for the inner section.

Tables

	R^2			RMSE (m)			Peak RMSE (m)			Perror (%)		
Recorder	0.01	0.015	0.019	0.01	0.015	0.019	0.01	0.015	0.019	0.01	0.015	0.019
Sunk Island	0.950	**0.996**	0.987	0.43	**0.12**	0.22	1.01	**0.16**	0.43	42.15	**6.86**	18.00
Grimsby	0.985	**0.998**	0.991	0.24	**0.10**	0.19	0.53	**0.14**	0.23	21.78	**3.20**	8.54
Immingham	0.949	**0.996**	0.979	0.45	**0.12**	0.29	0.93	**0.07**	0.32	36.77	**2.27**	12.58
King George's Dock	0.946	**0.993**	0.954	0.47	**0.17**	0.44	0.70	**0.04**	0.27	25.89	**1.08**	10.12
Albert Dock	0.947	**0.995**	0.956	0.47	**0.13**	0.42	0.65	**0.04**	0.32	23.89	**0.65**	11.56
Humber Bridge	0.934	**0.982**	0.933	0.50	**0.24**	0.50	0.30	**0.05**	0.30	10.24	**-0.11**	10.33
Blacktoft Jetty	0.820	**0.863**	0.819	0.78	**0.68**	0.78	0.50	**0.26**	0.51	15.40	**8.27**	15.89
Mean	0.933	**0.975**	0.946	0.48	**0.22**	0.41	0.66	**0.11**	0.34	25.16	**3.17**	12.43

Table 1 - Statistic measures comparing observed and simulated tidal heights for Week 48 of the calibration period, 2010. The optimal scores between the Manning's n roughness coefficient values is shown in bold.

Recorder	R^2			RMSE (m)			Peak RMSE (m)			Perror (%)		
	0.01	0.015	0.019	0.01	0.015	0.019	0.01	0.015	0.019	0.01	0.015	0.019
Sunk Island	0.996	0.998	0.990	0.17	0.12	0.25	0.24	0.21	0.29	4.84	4.06	5.80
Immingham	0.979	0.993	0.978	0.41	0.23	0.38						
King George's Dock	0.972	0.993	0.961	0.51	0.23	0.50	0.46	0.09	0.04	8.55	1.61	0.84
Humber Bridge	0.973	0.974	0.873	0.50	0.41	0.83	0.10	0.28	0.62	1.69	-4.64	-10.40
Blacktoft Jetty	0.934	0.836	0.706	0.71	0.99	1.13						
Mean	0.971	0.959	0.902	0.46	0.40	0.62	0.20	0.15	0.24	3.77	0.26	-0.94

Table 2 - Statistic measures comparing observed and simulated tidal heights for 5 December 2013.