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ORIGINAL PAPER

Understanding a coastal flood event: the 10th March 2008 storm surge event in the Solent, UK

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Abstract Extreme sea-level events (e.g. caused by storm surges) can cause coastal flooding, and considerable disruption and damage. To understand the impacts or hazards expected by different sea levels, waves and defence failures, it is useful to monitor and analyse coastal flood events, including generating numerical simulations of floodplain inundation. Ideally, any such modelling should be calibrated and validated using information recorded during real events, which can also add plausibility to synthetic flood event simulations. However, such data are rarely compiled for coastal floods. This paper demonstrates the capture of such a flood event dataset, and its integration with defence and floodplain modelling to reconstruct, archive and better understand the regional impacts of the event. The case-study event comprised a significant storm surge, high tide and waves in the English Channel on 10 March 2008, which resulted in flooding in at least 37 distinct areas across the Solent, UK (mainly due to overflow and outflanking of defences). The land area flooded may have exceeded 7 km^2, with the breaching of a shingle barrier at Selsey contributing to up to 90 % of this area. Whilst sea floods are common in the Solent, this is the first regional dataset on flood extent. The compilation of data for the validation of coastal inundation modelling is discussed, and the implications for the analysis of future coastal flooding threats to population, business and infrastructure in the region.

Keywords Coastal flooding · Inundation modelling · Model validation · Storm surge · Extreme sea levels · Sea-level rise · Defence failure · Return periods · Flood events

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1 Introduction

In Europe, developments in coastal flood risk management accelerated following the 1953 North Sea floods which killed 1836 people in the Netherlands, 307 in the UK and 17 in Belgium (Gerritsen 2005; Baxter 2005; McRobie et al. 2005) and floods on the German Bight in 1962 when more than 300 people lost their lives (Bütow 1963; von Storch and Woth 2006). Today, coastal planners benefit from a more developed understanding of the nature and degree of exposure to flooding due to advances in coastal modelling (e.g. Battjes and Gerritsen 2002) and flood risk assessments (e.g. Hall et al. 2003; Gouldby et al. 2008). Methods to generate realistic maps of inundation using geographical information systems (GIS) combined with remotely sensed data, and numerical models have been developed and widely applied (Pender and Néelz 2007). However, significant uncertainties remain when modelling coastal flooding across sources, pathways and receptors (Narayan et al. 2012), and the simulation of defence failure and associated inundation comprises a particularly sensitive and poorly integrated component of flood modelling. Hence, some form of validation is crucial.

A model is generally said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits or errors for a particular purpose (Hunter et al. 2007), whilst calibration can be applied to adjust parameters associated with a model, so that the model agreement is maximised with respect to observed data. Benchmarking studies for fluvial inundation have proved to be highly beneficial in determining the best modelling approaches for use in given situations and their potential prediction accuracy (e.g. Hunter et al. 2008). However, in many coastal areas, there is a lack of data and the necessity to improve the validation of inundation models is well recognised (Bates et al. 2005; Brown et al. 2007; Smith et al. 2012). To develop and comprehensively test models for coastal flooding, observations of flood inundation extent are required (Bates et al. 2005). Coastal flood model validation and sensitivity analysis using observed inundation extent can comprise the use of hard (i.e. tide gauge measurements, surveying of debris lines) or soft data (i.e. aerial imagery, photos, TV coverage and eye-witness descriptions) to reconstruct events (*c.f.* Bates et al. 2005; Gallien et al. 2011; Smith et al. 2012). This issue is not new but literature relating to this topic is surprisingly sparse. Compilation of such data is essential to validate coastal inundation modelling, especially for regions that have not yet been studied or coastal flooding is a worsening phenomenon (e.g. due to sea-level rise).

The case-study region described in this paper, the Solent in southern England (Fig. 1), experiences frequent coastal flooding, as explained in an analysis of extreme water level events and newspaper archives by Ruocco et al. (2011). Furthermore, rising sea levels mean that this is a region of concern for coastal flooding (Haigh et al. 2009, 2011). There has previously been ad hoc documentation of flood extents and consequences after several major events in the region. These include floods in the Lymington and Keyhaven areas of the West Solent in December 1989 (NRA 1990), and Eastoke on Hayling Island in November 2005 (HBC 2006). The 10th March 2008 event considered in this paper was reviewed in a regional assessment by the Environment Agency (EA 2010), a report which provides an essential foundation for this research; although as shown later a number of flooded sites were omitted. This study aims to synthesise the records for the 10th March 2008 event, including examining photographs and descriptions captured near high tide, to develop as complete a dataset on flood extent (FE) and consequences (number of houses flooded) as possible. Therefore, the overall aim of this paper is to define real flood cases from historic data and test modelling frameworks to replicate them. The objectives to achieve this are to:

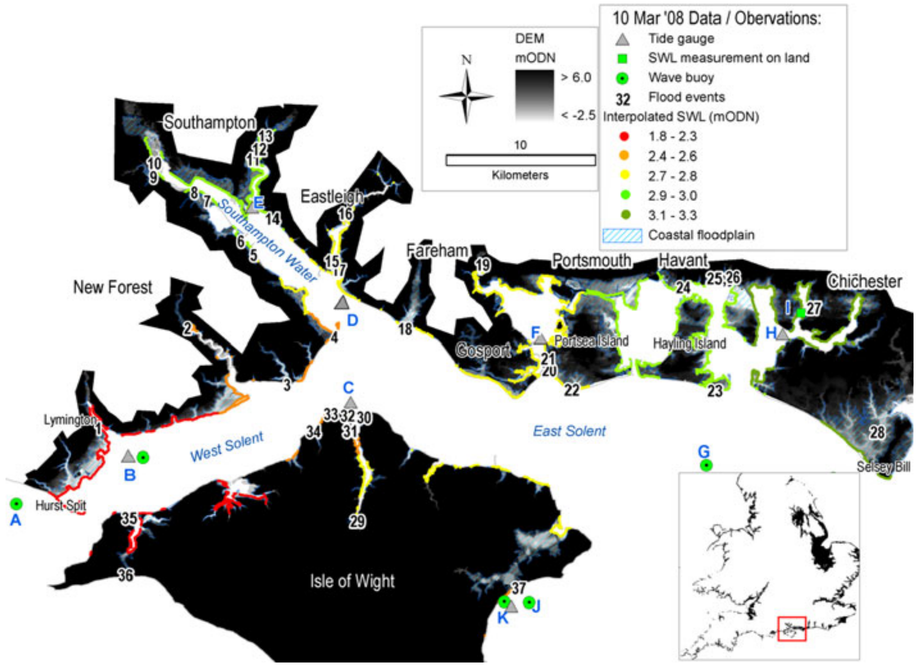

Fig. 1 The Solent case study and locations of wave, water level and flooding observations during the 10th March 2008 storm surge event. The locations labelled are observations of coastal boundary conditions (Table 1), flood events (determined by eye-witness accounts and photos of flooding, Table 2), and still water levels (SWLs) interpolated from the measurements. The digital elevation model (DEM) shows land heights referenced to metres above Ordnance Datum Newlyn (mODN). The base map (lower right) shows the 1 in 1,000 indicative coastal floodplain in England and Wales (DEFRA and EA 2004)

1. Summarise the existing nature and knowledge of flood events in the Solent study region;
2. Compile information and describe a regional flood event on 10 March 2008;
3. Describe the modelling methodologies and datasets;
4. Examine the validity of the model, including the interpretation of the number of properties flooded; and
5. Review improvements for data collection for future flood events.

A background to the case-study region and example flood event will now be described (Sect. 2), followed by the methodology (Sect. 3), results (Sect. 4), discussion of key findings (Sect. 5) and conclusions (Sect. 6).

2 Background

2.1 The Solent case-study region

The location of the study area, the Solent, is shown in Fig. 1. Key locations are marked, and the areas of lower topography, broadly at risk of coastal flooding, can be seen by the lighter coloured areas of the digital elevation model (DEM). Much of the Solent's shoreline

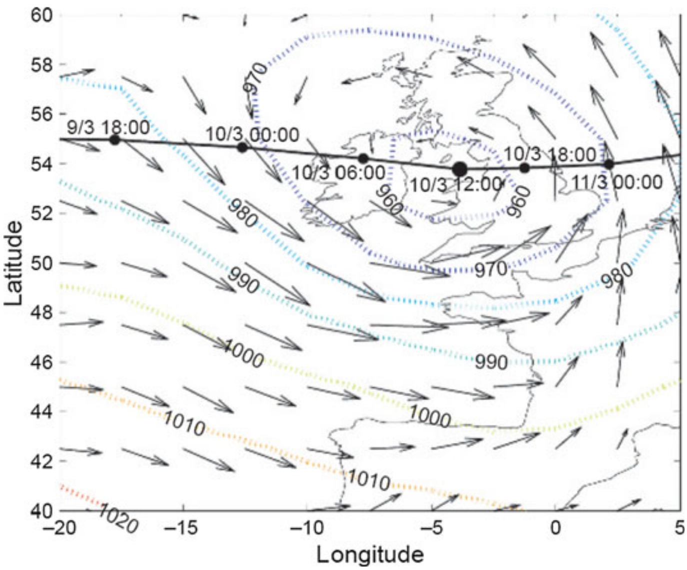

Fig. 2 Atmospheric pressure at 1200 h on 10 March 2008, over the British Isles and the approximate storm track. The arrows indicate wind direction and the dotted contours atmospheric pressure. Plot generated by Haigh et al. (2011) using the US National Centre for Environmental Prediction global reanalysis data

is sheltered from large waves by the Isle of Wight, and a managed shingle barrier at the western end known as Hurst Spit (Bradbury and Kidd 1998). The tidal range increases from approximately 2 m at Hurst to 5 m at Selsey, and the Solent is internationally renowned for its complex tides (Pugh 1987). The amplitudes of tidal components which are influenced by resonance in the English Channel and more localised shallow water effects (M_4 and M_6 constituents) are relatively large in the region, compared to the amplitude of the main semidiurnal lunar (M_2) tidal constituent. This results in double high waters in Southampton Water (which are particularly pronounced during large spring tides and at mid-flood) and extended high waters in the eastern Solent. Storm surges in the Solent mainly occur as a result of low-pressure systems that move from the Atlantic eastward over southern England (Haigh et al. 2004), whilst smaller surges also occur as a result of large North Sea storm surge events transmitted into the English Channel through the Dover Strait (Law 1975). Non-tidal residuals in the region rarely exceed 1 m, with only a 0.33-m difference between a 1 in 10 and 1 in 1,000 year water level (Haigh 2009; Haigh et al. 2011). Of significance to coastal flooding is that the Solent's defences are frequently subjected to prolonged hydraulic loading during storms due to the double high tides. The main spatially variable characteristics of storm tides in the Solent are demonstrated in Fig. 4 by the available still water level time series recorded during the case-study storm surge event of 10 March 2008.

The form and extent of the estuary has largely been controlled by changes in mean sea level until progressive development and land reclamation began in the eighteenth century. This was most significant around Southampton Water and Portsmouth; the two cities having grown together to form an urban area containing over one million inhabitants. The topography of the Solent currently allows there to be potential for coastal flooding along approximately 250 km of intertidal shoreline, and within almost 100 spatially discrete floodplains of variable size, configuration and level of flood protection. These ‘flood

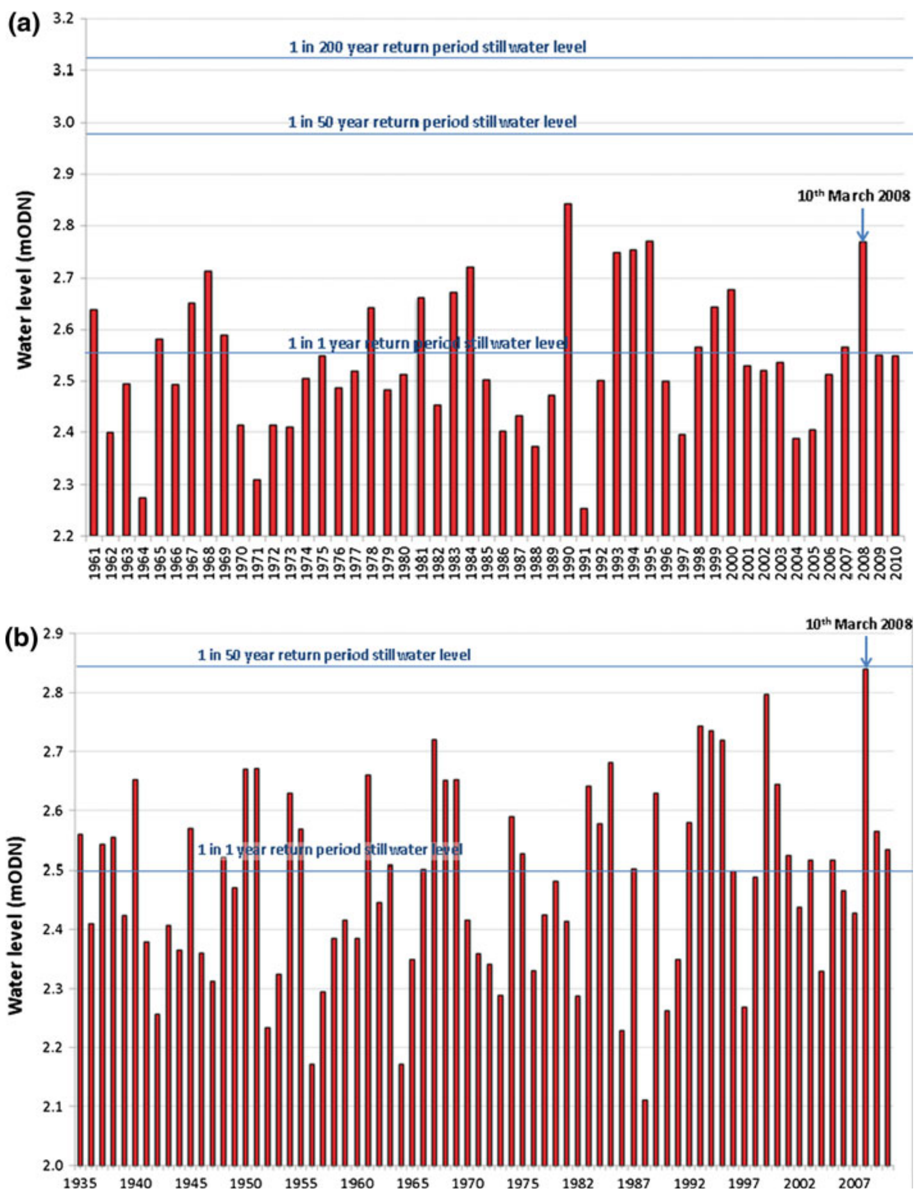

Fig. 3 **a** Plot of the highest annual still water levels recorded since 1961 at Portsmouth, shown in relation to the 2008 return period still water level (SWL) elevations. The SWL dataset is provided by Haigh et al. (2009), return periods from Mcmillan et al. (2011). **b** The highest annual still water levels recorded since 1935 at Southampton. The SWL dataset and return periods are from Haigh (2009)

compartments' are simply defined as land areas that if flooded, are likely to remain separate during an extreme still water level event. Without considering defences or the dynamics of flooding, more than 24,000 properties are exposed to a 1 in 200 year still water level coastal flood (NFDC 2009; Wadey et al. 2012). Around half of the Solent's

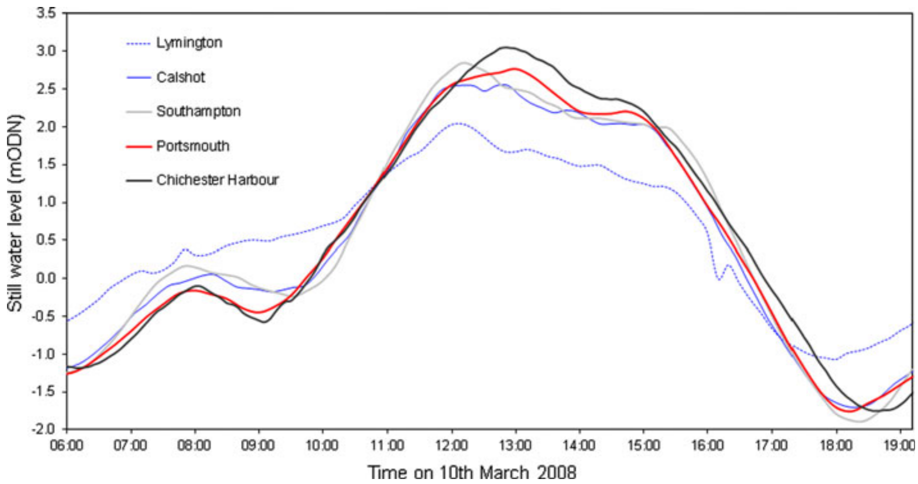

Fig. 4 Still water level time series recorded across the Solent on 10 March 2008

shoreline is comprised of defence systems where a reduction in crest height (breach) could significantly exacerbate flooding over a wider area; whilst along the remaining shoreline defences are more ad hoc, including structures and natural features which locally mitigate overtopping and control erosion. More than half of the Solent's property exposure to coastal flooding is in Portsmouth (Wadey et al. 2012), which after London and Hull contains the most properties exposed to coastal flooding for any city in the UK (RIBA and ICE 2009). Sea defences surround Portsmouth's 45 km coastline, 25 % of which are estimated to provide less than the 1 in 200 year level of protection recommended for UK urban areas (Atkins 2007). The Solent's other city, Southampton, has almost no coastal flood defences but fortunately has low coastal flood risk at present sea levels. The level of protection for many of the Solent's defended rural and urban areas is variable, and often very much dependent upon ongoing maintenance. For example, a 1 in 200 year standard of protection is targeted along the Eastoke frontage (southeast Hayling Island—Fig. 1), primarily by beach management operations (e.g. beach recharge, maintenance of groynes) (e.g. HBC 2013a, b). In many locations where coastal structures are present and crest heights have not been raised in recent decades, these are currently likely to remain functional as flood defences during approximately the 1 in 25 to 1 in 50 year annual probability events (*c.f.* NRA 1990; Wadey et al. 2012).

Meteorological-induced sea-level effects on the UK south coast are generally less severe than on the east and west coasts, although surge events (Wells et al. 2001; Haigh et al. 2011) and Atlantic swells (Mason et al. 2009) have been associated with coastal flooding. Coastal flood events in the Solent since the mid-twentieth century are summarised by Ruocco et al. (2011) in a study which combined extreme water level events and corresponding newspaper records of flooding. This dates back to 1935 at Southampton and to 1961 at Portsmouth, using data by Haigh et al. (2009). This revealed that flooding frequently occurs in the region, with parts of Southampton, Portsmouth, Hayling Island, Fareham and Cowes being particularly flood prone. Inundation events over the last 50–60 years have mostly been minor with no loss of life, and the most significant storms were during 13–17 December 1989, when high water levels persisted over eight tidal cycles (Wells et al. 2001) and 21 locations flooded (Ruocco et al. 2011). Despite rising sea levels, the incidence of flooding has tended to decline due to both fluctuations in storminess (Haigh et al. 2010) and improvements in flood defences in the most vulnerable areas (e.g. a beach renourishment project at Eastoke, Hayling Island in 1985). Anecdotal evidence suggests that more significant events occurred in the eighteenth and nineteenth centuries (West 2010), although again no human loss of life in the Solent is reported. Looking to the future, a national assessment of flood risk identified that the South coast could experience some of the largest increases in flood risk during the twenty-first century due to rising sea levels and population growth (Evans and Office of Science and Technology 2004).

2.2 The 10th March 2008 storm surge

This paper focuses on the storm surge event which occurred on 10 March 2008, which generated the highest recorded water level at Southampton since 1935 when 15-min tide gauge data begin. This event has been briefly described by Haigh et al. (2011). On 9 March 2008, a strong jet stream across the north Atlantic created a deep low depression off southeast Greenland. As this moved SE over the northern Atlantic, the central pressure dropped rapidly from 975 mb at 0600 h (9 March) to 946 mb 18 h later. The central pressure remained very low as the system moved over Ireland, across the Midlands and into the North Sea. The path of the storm is shown in Fig. 2 and was typical of storms that tend to generate large surges in the English Channel (Henderson and Webber 1977). A high spring tide was predicted for the 10th March and the time of high tide coincided with the passage of the centre of the storm. As the event passed over Ireland and England, the low-pressure and strong south–west to westerly winds generated a surge of around 1 m in the central regions of the English Channel. Skew surge—that is, the difference between predicted and observed high water (Horsburgh and Wilson 2007)—exceeded 0.7 m at six stations: Weymouth, Southampton, Portsmouth, Jersey, Cherbourg and Le Havre. Further east in the English Channel, the surge was much smaller.

Localised flooding occurred in the western and central Channel including Teignmouth (Devon), Flushing (Cornwall) and in several small towns along the Brittany coastline, whilst in the Cornish town of Perranporth firefighters had to pump seawater from a pub and several businesses (BBC 2008c). Flooding was extensive in the Channel Islands; in Jersey, the damage to sea defences was estimated at about half a million pounds (Le Blancq and Searson 2008). Flooding also affected Poole in Dorset, forcing road closures and threatening valuable property (BPUA 2011).

In the Solent, the storm surge peak and tidal high water coincided across most of the region: the available still water level time series records in the Solent for this event are shown in Fig. 4. The time of high water was approximately 12:00 at Lymington, 12:30 at Southampton, 13:00 at Portsmouth and 13:30 at Selsey Bill. Flood warnings were delivered in most of the affected areas (EA 2010) and the daytime occurrence of this event allowed the public to respond by moving possessions and building temporary defences. Most flooding was relatively minor, although there were numerous road closures and more than 30 properties were reported to have flooded (12 requiring evacuation) (EA 2010), and a holiday park in the flood plain at Selsey was evacuated (BBC 2008a) in what was the most dramatic incident that occurred during the event. This was caused by substantial lowering of an 800-m section of the shingle barrier beach (Cope 2012). On the other hand, new defences at Portsmouth and Lymington prevented serious flooding in areas which had previously flooded during similar events. No sea walls or embankment structures in the region were reported breached (where breach is defined by formation of an aperture or a reduction in the crest height of a defence). The onset of the flooding from overflow, overtopping and outflanking of defences was, however, quite rapid, and reports by local resident associations suggest that the event initiated concern about the impacts of climate change and the need to improve flood event management procedures (e.g. West 2008; YCDWG 2010). The event came close to causing more significant impacts in the Solent's cities, with still water levels within centimetres of flowing onto Southampton's Docks (Haigh et al. 2011; Wadey et al. 2012); and in Portsmouth reportedly leaving Southsea's Rock Gardens 'under up to nine inches [0.23 m] of seawater for the first time in the past 60 years (The News 2008a).

Figure 3a and b places the 10th March 2008 event into an historic context. The peak still water level on 10 March 2008, approximated a 1 in 20 year event at Portsmouth and a 1 in 50 year event Southampton (Haigh et al. 2011): recently revised return periods (McMillan et al. 2011) suggest that the still water level was less than a 1 in 10 year return period event at Portsmouth. The 10th March 2008 still water levels peaked at 2.77mODN at Portsmouth and 2.84mODN at Southampton (Table 1): the highest water level at Southampton since 1935. Extreme water level events prior to the data shown in Fig. 3a and b include a water level of 2.86mODN (5.6 m Chart Datum) at Southampton on 27 November 1924 (ABP 2010); and 3.2mODN at Portsmouth in 1840 (Easterling 1991). The exact date or accuracy of the 1840 Portsmouth recording is unknown, although a notable flood event is documented in the city that year (Sherwood and Backhouse 2012).

As noted in Table 1, not only were still water levels high during the 10th March 2008, but wave action was also significant. The importance of waves for flooding in some parts of the Solent is illustrated by the flooding that occurred at Eastoke (southeast Hayling Island, Fig. 1) on 3 November 2005, when a high sea-level event (with a peak of 2.44mODN at Portsmouth) combined with long period swell wave conditions (> 18 s) to rapidly erode and overtop the managed shingle beaches which protect numerous properties (HBC 2006; Mason et al. 2009; Ruocco et al. 2011) causing more severe flooding at this location than occurred on 10 March 2008 (both wave events have been analysed in detail by Palmer 2010). The complex and prolonged surge event of 13–17 December 1989, (Wells et al. 2001; Ruocco et al. 2011) was the worst storm surge flood event in the Solent in the last 50 years, despite the still water level at Portsmouth not exceeding 2.48mODN (less than a present-day annual extreme). Hurst Spit was breached and there was major flooding in Pennington/Lymington and Old Portsmouth. This suggests the need for further analysis of this event and the possible significance of multiple and interacting flood-causing mechanisms, related to the duration (as well as the height) of surge events, local wind and wave conditions, and interactions with non-coastal flood sources and pathways. However, detailed regional information about the December 1989 event (e.g. flood event outlines and reports, details of flooded property locations and impacts, wave data, defence details such as crest heights) have largely been lost, emphasising the benefit of the exercise being conducted here for the 10th March 2008 event.

3 Reconstruction and analysis of the 10th March 2008 event

The main stages of the analysis undertaken in this paper are summarised in Fig. 5. Boundary conditions required to simulate the 10th March 2008 event, were extracted from the tide gauge records and spectral wave data (refer to Table 1, Figs. 1, 4), and converted to inputs for a numerical model which simulated inundation across the Solent's floodplain throughout a single tidal cycle. The subsequent grid of water depths was then compared to

Table 1 Measured peak water levels and waves on 10 March 2008

Location ref in Fig. 1	Tide gauge/ measurement location	Peak still water levels		Peak wave conditions (CCO)		
		Recorded water level (mODN) and source of data	Approx. return level	H_s (m)	T_p (s)	Range of annual max. H_s (m) recorded 2003–2008
A	Milford upon Sea			3.42	11.0	2.92–4.09
B	Lymington	2.04 (CCO); 2.17 (EA)	1 in 10	3.42	11.0	0.81–1.44
C	Cowes	2.63 (EA); 2.61 (CHM)	1 in 10			
D	Calshot	2.55 (ABP)	1 in 5			
E	Southampton	2.88 (EA); 2.84 (ABP)	1 in 20			
F	Portsmouth	2.77 (BODC)	1 in 10			
G	Hayling Island			3.79	8.3	2.68–3.79
H	Chichester Harbour	3.1 (CHIMET)	1 in 20			
I	Bosham (Chichester Harbour)	3.3 (West 2008)	1 in 50			
J	Sandown Bay			3.63	8.3	2.79–3.79
K	Sandown Pier	2.52 (CCO)	1 in 5	1.62	10.6	1.82–2.01

Locations are referred to in Fig. 1. The data were provided by the Channel Coastal Observatory (CCO), Environment Agency (EA), Cowes Harbour Master (CHM), Associated British Ports (ABP), chimet.co.uk (CHIMET); and a land-based measurement in Bosham (West 2008); the return period is for the year 2008, approximated according to analysis by McMillan et al. (2011). H_s is the significant wave height, T_p is the peak period (as recorded during the same tidal cycle of the highest water levels)

observed flood extent, and was also used to extract water depths at properties (from a database of commercial and residential buildings in the Solent).

3.1 Flood datasets and modelling

Flood event data were compiled from an ad hoc series of reports and photographs collected by the media, members of the public and an Environment Agency assessment (EA 2010). Flood locations are summarised in Table 2 and Fig. 1. With no formal measurements of flood extent, these sources are of varying reliability although some are quite descriptive (e.g. noting names of buildings and roads affected, flow routes and water depths). Within

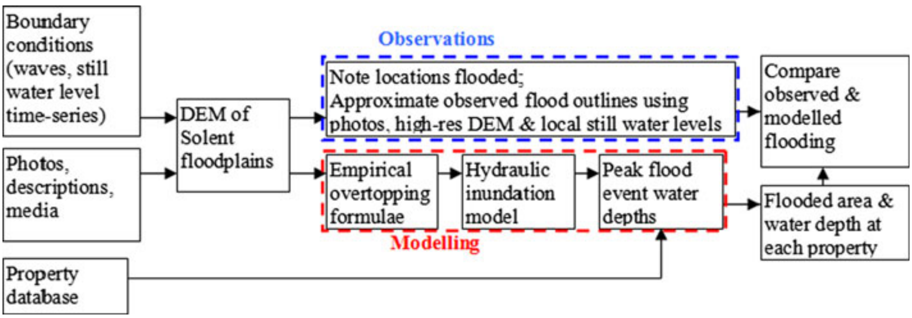

Fig. 5 Methodology: floods were modelled and compared to observations on 10 March 2008

geographical information systems (GIS), detailed land-use maps were overlain with a digital elevation model (DEM), coastal still water levels and flood defence datasets, allowing some flood outlines to be digitised to a reasonable level of confidence (whilst some areas are simply noted as flooded). Recent aerial photography and Google's Street View also benefitted the interpretation of the roads and areas identified in the flood event images and reports, to subsequently reconstruct flood extents.

The DEM was constructed from Light Detection and Ranging (LiDAR) surveys, processed in the format of a digital terrain model (with artefacts such as buildings removed). The LiDAR data were collected in 2007 and 2008 at 1–2 m spatial resolution, with accompanying metadata indicating that the root mean square error (RMSE) of survey points was better than 0.10 m (although $\pm$ 0.15 m vertical accuracy is often associated with topographic LiDAR data). Distances between the 10th March 2008 sea-level measurements were relatively large, and gaps were filled to provide a higher resolution water level dataset for inundation modelling. This was achieved by linear interpolation—in some locations benefited by a knowledge of typical spatial variations in extreme water levels indicated by the dataset developed by McMillan et al. (2011) which comprises 2 km spaced points along the coast (each associated with a range of water level return periods derived from a combination of the skew surge joint probability method and the CS3X hydrodynamic model). Recorded wave heights and periods (Table 1) were interpolated and scaled spatially in proportion to calculations of fetch-limited conditions within the harbours and rivers.

The inundation event was numerically simulated using the methodology described in Wadey et al. (2012), where inflows from 5,000 shoreline locations were determined by a detailed database of shoreline defences (crest heights, geometry, layout, etc.), overtopping calculations and coupled to a hydraulic inundation model. The numerical inundation model used was LISFLOOD-FP, a raster-based code which simulates floodplain flows in 2D using an analytical formulation of the shallow water equations. Variants of this model have previously been used to simulate coastal flooding (Bates et al. 2005; Purvis et al. 2008; Smith et al. 2012). Technical details of the older diffusive flood-wave version are provided in (Bates and De Roo 2000); whereas here, a newer version is applied based upon an inertial formulation of the shallow water equations as explained by Bates et al. (2010). With good quality topographic data storage cell models such as LISFLOOD-FP can produce similar results to full 2D formulations of the shallow water equations (for sub-critical gradually varied flows only) (*c.f.* Néelz et al. 2009). LISFLOOD-FP was set-up to utilise the LiDAR data's representation of the Solent's floodplain topography interpolated to 50 m cells for computational efficiency and because this resolution is commensurate with most of the available shoreline flood defence survey data. Some allowance was made for DEM error by excluding analysis of flooding in cells where water depths were less than 0.05 m (*c.f.* Hunter et al. 2008). Calibration using friction coefficients is important to such models, although the greatest uncertainty to coastal inundation models can be defence failure inputs such as wave overtopping (Smith et al. 2012), whilst other defence failure elements that can be integrated into flood modelling such as breach analysis also remain highly uncertain (e.g. Morris et al. 2008). These aspects are briefly discussed in the subsequent sections of this paper.

3.2 Validation

Thirty-seven locations were observed to flood (Table 2). These observed floods were compared to model results by the following methods:

Table 2 Flood locations on 10 March 2008

Location no.	Sub-region	Flood compartment/ area	Site recorded as flooded	Likely flood extent (km^2)	Mechanism	Model performance (F_A) and whether under-/over-predicted	Main source of observations
1	New Forest	Lymington	Quay street	0.002	OF	0.90	EA (2010)
2		Beaulieu	Palace Lane	0.032		0.90 OP	
3		Lepe	Lepe Road	0.025	OT	0.75 UP	
4		Calshot	Calshot Road	0.042	OF	0.60 OP	
5		Hythe	Shore Road and Sailing Club	0.069		0.78	
6			The Promenade and Prospect Place	0.022		0.56	
7			Marchwood: Cracknore Hard	0.017		0.42 UP	
8			Marchwood: Magazine Lane	0.014		0.29 OP	
9		Totton	Eling: Down's Park Crescent and Down's Park Road	0.068		0.97	
10			Commercial Road	0.007		0.88	
11	City of Southampton	Southampton East	River Itchen: Saltmead	0.004		0.92	
12			River Itchen/St Denys: Priory Road	0.004		0.57 OP	
13			River Itchen: Woodmill Lane; Oliver Road	0.028		0.38 UP	SCC (2010); EA (2010)
14		Weston to Woolston	Weston Shore: Weston Parade	0.025	OT	0.55	Southern Daily Echo (2008)
17	Fareham	Warsash and east River Hamble	Passage Lane and Shore Road	0.017	OF	0.80 UP	EA (2010)
18		Hill Head	Unknown—"driver had to be rescued by firefighters from his car when it was swamped by water".	N/A	OF, OT	Model indicates 2 pixels of flooding of ~30 cm depth on road	The News (2008b)
19		Wallington	Wallington Shore Road and Delme Drive	0.022	OF, NC	0.2 UP	FBC (2011); WVCA (2011)
15	Eastleigh	Hamble	Rope Walk, Well Lane and Green Lane	0.005		0 UP	EA (2010)
16			Bursledon: Blundell Lane	0.026		0.65 UP	

Table 2 continued

Location no.	Sub-region	Flood compartment/area	Site recorded as flooded	Likely flood extent (km^2)	Mechanism	Model performance (F_A) and whether under-/over-predicted	Main source of observations
20	City of Portsmouth	Old Portsmouth	East street and, Broad street; flooding at ferry terminal and buildings at Camber Quay	0.016	OF, OT	0.50 OP	BBC (2008b); EA (2010)
21		West Portsea	The Hard ("car engulfed near slipway opposite the Ship Ansom pub").	N/A		Model indicates a single flooded pixel of ~70 cm water depth	The News (2008b)
22		Southsea	Clarence Esplanade (including the 'Rock Gardens')	N/A	OT	Model indicates shallow (~10 cm) patches of water in the rock gardens and on Southsea Common	The News (2008a); PCC (2009)
23	Havant	Eastoke, Hayling Island	Southwood Road, Creek Road, Nutbourne Road and Bosmere Road	0.022		0.15 OP	EA (2010)
24		Langstone/ Havant Mainland	High street; the car park of 'The Ship' pub sea water "trapped customers and staff vehicles".	0.048	OF	0.50 UP	The News (2008b); EA (2010)
25		Emsworth	Bridge Road Footpath, Bath Road and Mill Pond	0.067		0.86 UP	EA (2010); ERA (2008)
26			A259, Queen street and Lumley Road	0.034		0.42 UP	
27	Chichester	Bosham	Shore Road, Bosham Lane, Stumps Lane, The Drive, High street and Harbour Road	0.077		0.95	West (2008); Chichester Observer (2008a)
28		Selsey	West Sands Caravan Park (30 people evacuated, 100 caravans damaged)	N/A	OT, BR	4.7–8.6 km^2 indicated inundated by range of modelling methods	BBC (2008a); Cope (2008); Chichester Observer (2008b)

Table 2 continued

Location no.	Sub-region	Flood compartment/ area	Site recorded as flooded	Likely flood extent (km^2)	Mechanism	Model performance (F_A) and whether under-/over-predicted	Main source of observations
29	Isle of Wight	Newport Town Centre	Medina Way, Sea street and The Quay	0.027	OF, NC	0.33 UP	EA (2010); IRF (2011); Hodgson (2012); Wearmouth (2012)
30		East Cowes	Esplanade	0.012	OF, OT	0.91	
31		West Cowes	Brunswick street, Medina Road, Bridge Road, Fountain and Town Quays, High street, Red Funnel Ferry Terminal	0.060		0.62 UP	
32			Egypt and Princes Esplanade	0.026		NK	EA (2010); IOWCP (2008)
33			Marine Parade	0.004			
34		Gurnard	Marsh Road and Rew street	0.016			
35		Yarmouth	Bridge Road, Quay street, The Quay and River Road	0.093	OF	0.85 UP	EA (2010); YCDWG (2010)
37		Eastern Yar	Yaverland Road (sea water flooded car park at 'Dinosaur Island)	N/A (but > 0.005)	OT	Model indicates shallow flows (<10 cm) behind seawall, similar to photos, although full extent unknown.	Price (2013)
36			Freshwater Bay	N/A ($\sim$0.001)		Model indicates a flooded pixel of $\sim$20 cm water depth	IOWCP (2008)

1. *Simple binary comparison*: it was noted whether or not the model generated flooding within the same flood compartment within which flooding had been reported;
2. *Photos and/or descriptions*: in some locations these allowed an approximation of the flood outline to be digitised. This allowed modelled and observed coastal flood extents to be compared using a fit measure (F_A) as defined and used in previous coastal flood modelling studies (Bates et al. 2005; Gallien et al. 2011). This comprises the intersection and union of predicted (E_p) and observed (E_0) flooded pixels. A value of zero corresponds to no agreement, a value of 1 to perfect agreement:

$$F_A = \frac{E_P \cap E_0}{E_P \cup E_0} \quad (1)$$

At each location, a record was also made as to whether the model under- or over-predicted flooding; and where the model generated flooding, the depth was also recorded. Although the validation data did not in most cases contain sufficiently detailed information to verify these aspects, it could be noted if the model produced unrealistic depths or floods that would have been severe enough to warrant significant mention (e.g. in the media reports).

3. *Number of flooded properties*: specific locations of most of the properties affected by flooding were not available. It was suggested by EA (2010) that at least 30 properties experienced flooded interiors, but as is discussed in the following section there is considerable uncertainty over how thoroughly floods were reported, and viewing photographs from the flooded locations suggested that over 150 buildings were in contact with flood waters; whilst a number of caravans were also flooded at Selsey.

Limitations to this exercise include the superimposition of the curved flood extent polygons upon the relatively large pixels (50 m) of the raster grid which was used for the inundation modelling. For example, the width of land flooded in some incidences comprised long, thin linear strips (narrower than 50 m) and in such cases over-prediction or under-prediction by the model (as referred to in Table 2) was considered negligible unless more than one full flooded cell was outside of the observed extent. The F_A method and large pixel size also meant that in cases of good model fit (e.g. $F_A > 0.75$) not all values qualified as over- or under-predictions (as noted in Table 2).

4 Model results and observations

Figure 1 shows flood event locations, which are listed in Table 2. The model fit scores (F_A) shown in Table 2 are for the modelled flood outline generated by the 50-m resolution application of the inundation model; comprising: (1) a spatially heterogeneous floodplain friction (Manning value) of 0.035 (an average value based upon land classification in the Solent), (2) crest height data (mainly from ground-based surveys using RTK GPS) and (3) inflows from the still water levels (Fig. 4) and waves (combining relevant empirical overtopping formulae and defence parameters). The flood extents were too small to justify calibration and a fuller analysis of uncertainty; whilst the extent of the largest flood on the day at Selsey (at the eastern end of the Solent, refer to Figs. 1, 6) is uncertain. The maximum likely theoretical extent at Selsey, gained from laying the nearest known water level (3.3mODN) as a planar surface across the DEM generates a flood extent of almost 8.8 km^2. Alternatively, using the numerical inundation model to route the nearest recorded still water level time series through the approximated breach area generates flooded land areas of between 4.7 and 5.8 km^2, from the application of friction coefficients (n) of 0.06 and 0.035, respectively. The inclusion of wave overtopping volumes generates flood extents of 6.5–8.6 km^2 for the same range of surface friction values. These results are based upon various simplifications, including that the breach size (which is only an estimate) is assumed to be fixed for the duration of the tidal cycle, providing greater inflow through the breach than reality. However, the numerical simulations did generate a plausible representation of water depth across the locations where flooding observations were available (Fig. 6).

The model was not formally calibrated, and we used a simple addition method to account for the effects of the significant amount of rainfall upon the upper reaches of the tidal rivers. The best results were produced by adding 10 cm to the boundary water levels at the upper tidal reaches of the region's rivers, and this is included in the results shown in Table 2. Locations 2 and 29 (where floodplain flows were reportedly quite shallow) could not be flooded by the model without this additional still water level, which suggests possible tide locking of fluvial flows or amplification of the surge; whilst location 15 could not be flooded even with this additional water level—this is discussed further in Sect. 5 of this paper.

The official flood event report (EA 2010) suggests that 30 properties were affected. Whilst this source provides essential background information for this study, the omission of various flooded locations discounts it as a comprehensive quantification of the number of properties flooded, and is likely to be an underestimate. For example, it was also reported in Bosham (location 27) that the EA were unable to incorporate third-party reporting of flooded properties. Here, we apply an extended understanding of the number of properties close to or in contact with flood water, using the compilation of flood event outlines listed in Table 2.

Table 3 summarises flooded land area, the model's performance and the number of properties indicated to be close to flood water. The photos taken during the event cover 30 of the 37 reported flooded locations. These indicate that at least 150 properties were in contact with water (e.g. Fig. 7 suggests that a minimum of three separate buildings are surrounded by water). The 'view' of flood extents provided in these photos was extended by digitising flood outlines (in GIS) along the path of the likely flooded area (roads, etc., aided by descriptions and the DEM). These polygons indicate that 342 properties were in contact with the flood waters (although as noted in Table 3, this estimate increases substantially if the polygon is slightly extended). The flood outline generated by the simulation contains more than 1,000 properties, although because the altitude of the flood-water entry thresholds for each property is not known it is unsurprising that this is an overestimate, especially given other uncertainties (e.g. vertical error in the original LiDAR data and boundary inputs).

Therefore, using the model to provide a realistic estimate of properties that could be considered actually or nearly flooded; the simulation's inundated pixels should be filtered by depth (rather than counting all of the properties within the raw flood outline). Table 4 summarises the depth filter that is required for the number of properties within the simulated flood outline to match the number of properties in the observed flood polygon. This only considers the locations where photographic evidence is available. It is noted in flood impact guidelines assessment guidelines (e.g. Penning-Rowsell et al. 2005) that approximately 20–30 cm is a typical threshold depth for water to enter property. This approximation is valid in some locations for the 10th March 2008 Solent event, although larger depth 'cut-offs' are required in some locations. The simulation's greatest overestimation of the total number of flooded properties is on the densely urbanised Eastoke Peninsula on

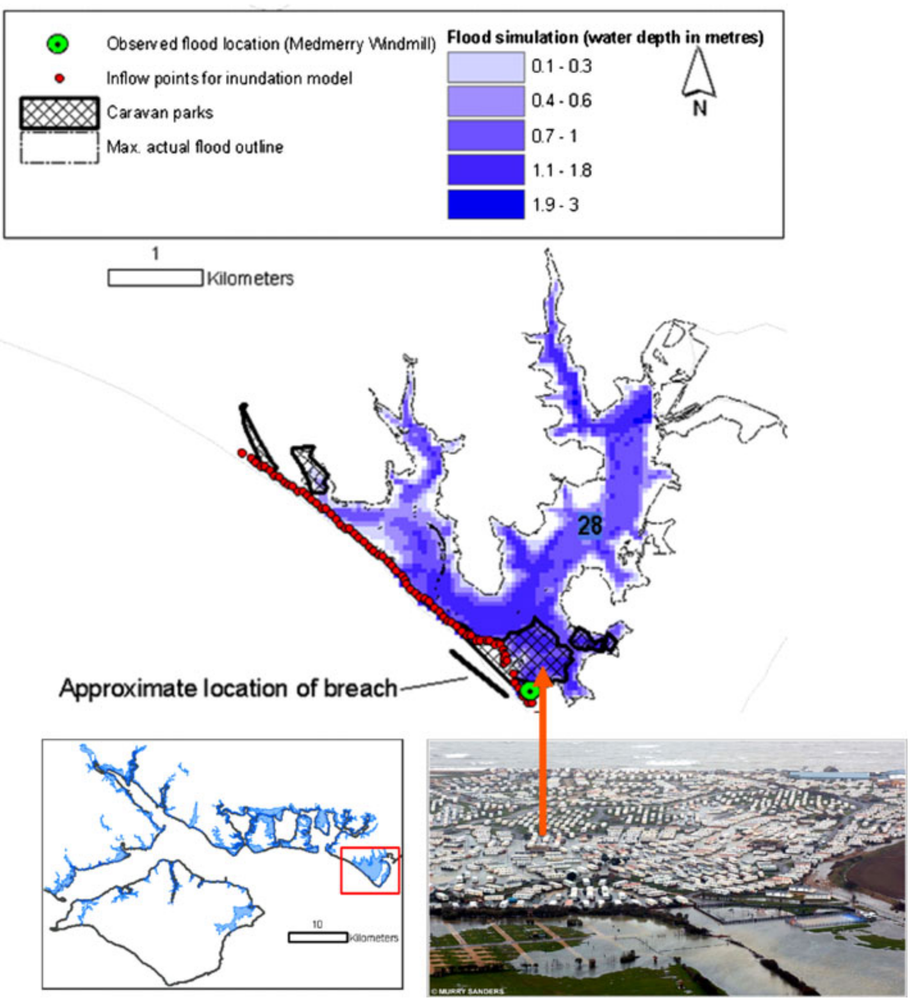

Fig. 6 Flooding at Selsey, where waves overtopped and partially breached the shingle barrier. The photo shows flooding at a caravan park on 10 March 2008 (The Mail 2008). The main 'Broad Rife' floodplain was reported in Chichester Observer (2008b) to be "full and overtopping to the west, for the first time in 48 years". The observed flooded building location is where flood waters reportedly reached the base of the historic Medmerry Windmill (West 2010) which lies on the vertices of two cells with simulated peak flood depths of 0.15 and 0.70 m. The map location (lower left) also shows the Solent's potential 1 in 200 year coastal floodplain (without considering defences or flood dynamics)

Hayling Island, Havant, where available reports and photos suggest that wave overtopping caused shallow flooding on several streets, but no property impacts. Flood predictions here are sensitive to the inaccuracies in the empirical overtopping calculations, lack of parameterisation of sub-surface drainage and over-spreading of flood water on the coarsened DEM (which did not incorporate buildings), generating a poor F_A score and showing more than 350 properties in the overall flood simulation outline. However, the flooded property count here reduces substantially if considering only water depth pixels above 0.25 m, and to zero above 0.5 m.

Table 3 Summary of the observational data and modelling used to reconstruct the 10th March 2008 coastal flood event in the Solent; including estimates of flooded area and property

Sub-region	No. of flooded locations	Observed land area flooded (km^2)	No of photos available	Properties in contact with floodwater according to source						
				Photos	Digitised polygon (and with 10 m buffer)	Numerical simulation: water depth filter (m)				
						Total	0.25	0.50	1.00	1.50
New Forest	10	0.30	54	18	28 (59)	136	82	32	6	0
Southampton	4	0.06	20	12	21 (51)	139	21	6	4	1
Eastleigh, Fareham and Gosport	5	0.08	4	16	16 (70)	36	27	18	7	3
Portsmouth	3	0.06	2	2	5 (21)	62	2	2	0	0
Havant	4	0.17	93	61	65 (258)	411	71	24	1	0
Chichester	2	6.65	18	20	179 (260)	155	121	100	78	49
Isle of wight	9	0.25	94	27	28 (73)	154	115	88	33	10
Total	37	7.65	286	156	342 (792)	1093	439	270	129	63

The right-hand columns show the number of properties counted as flooded by the numerical simulation as a function of water depth. Caravans at Selsey (Fig. 6) are excluded from the analysis and observations, and the flood extent shown (6.65 km^2) is the middle estimate from the breach and overtopping simulations described at the start of Sect. 4. Refer to Fig. 1 for the location of these sub-regions

Fig. 7 Flood waters surround properties (near the time of high water) at Yarmouth, Isle of Wight on 10 March 2008 (*source* Yarmouth Coastal Defence Working Group)

The model fit score (F_A) indicated that predictions of flooding in relation to the flood event data were reasonable, with most instances of poorer comparison occurring for narrow strips of floodplain. This could be improved simply by using a less interpolated version of

Table 4 The 'depth criteria' required to evaluate the model's predictions of flood depth at properties, and a summary of the number of cases of under-prediction (UP) and over-prediction (OP) of flood extent (FE) by the simulation

Sub-region	Average depth criteria for model outputs	Average F_A value	UP	OP	Comments upon model performance
New Forest	0.40	0.94	2	3	Flood outlines recreated well, therefore 40 cm is perhaps a reasonable approximation to flood water being able to surround property
Southampton	0.25	0.61	1	1	Mostly shallow flows, some of which could be captured better with finer DEM
Eastleigh, Fareham and Gosport	0.65	0.50	3	0	Worst known flooding was in Wallington (northwest Portsmouth Harbour), and where the simulation under-predicted this flood—most likely due to the given sea-level boundary conditions and/or rainfall run-off
Portsmouth	0.11	0.50	0	1	Too many flooded pixels at Old Portsmouth predicted by the model (overtopping), although most indicate <20 cm depth
Havant	0.17	0.48	3	1	Greater depth filtering required at Eastoke, and less at Emsworth. The poor fit is due to under-prediction of FE at Langstone High St and over-prediction at Eastoke comprises (both improved using a higher resolution DEM); part of Emsworth flood was under-predicted due to possible influence of non-coastal flood source
Chichester	0.72	0.95	0	0	For the two locations (Bosham and Selsey), there is a good match between observed and predicted flood (using mid-approximation of the large flood at Selsey), although quite a substantial depth filter required to avoid over-prediction of flooded property
Isle of Wight	0.75	0.68	3	0	Finer resolution appropriate for delineation of flood extents on roads in Cowes
Solent	0.49	0.67	12	6	

This is based on locations in Table 2 where photographs depicting the event are available (and comparing with the digitised polygons developed from these photos)

the DEM (e.g. Fig. 7 shows flooding in the town of Yarmouth, Isle of Wight, and Fig. 8 is an inundation map generated from a 10-m resolution DEM), which enables a more accurate representation of topography and hence water depth distribution. This is especially beneficial for depicting flow on narrow floodplains and individually flooded roads; although uncertainty in the observation data and the overtopping inputs does suggest that this is likely to offer significant advantages for all areas. Generally, the best match between the simulated and observed flood extent was noted in less urban areas, and where significant wave action was not involved. The under-prediction of flood extent (and properties) was most apparent at locations 15, 19, 26 and 29 (refer to Table 2), whilst defence failure inflows generated some uncertainty for flood extent predictions on the open coasts of Selsey and Eastoke (Hayling Island). For future flood modelling, particularly at Eastoke and the tidal river locations, spatial resolution and boundary water levels should be

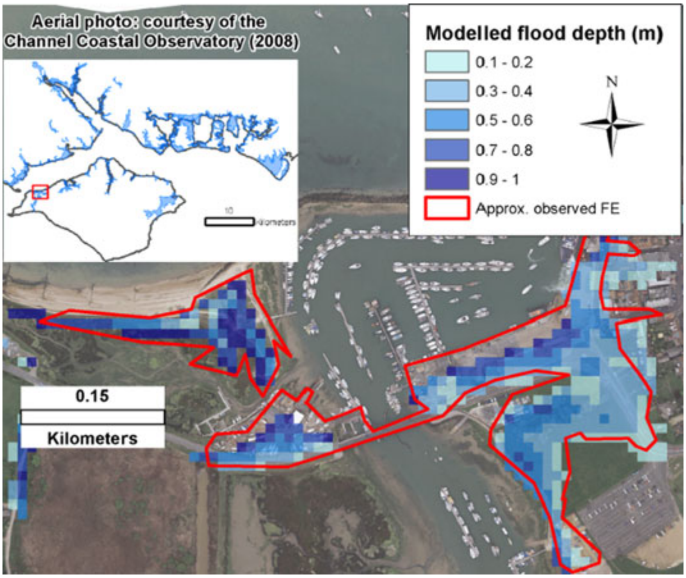

Fig. 8 Observed and modelled flood outline at Yarmouth on the Isle of Wight using a 10 m resolution model

reviewed (e.g. surge propagation and non-coastal flood sources may be significant to the occurrence and impacts of coastal flooding).

Across the region, it is probable that flood waters threatened more locations than reported. For example, enlarging the digitised polygons of observed flood extents (generated by the photos and descriptions) by applying a 10-m buffer provides a fuller coverage of areas threatened by flooding (e.g. gardens, driveways) and suggests that in excess of 700 properties may have been near or in contact with flood water (Table 3). Walls, fences, raised floor levels and flood prevention measures (e.g. sandbags) would have reduced the number of incidents where floodwater entered and damaged the interiors of buildings, and incidents such as flooding of outbuildings and gardens may not have been reported. The simulation further indicated that aside from the incidents mentioned in Table 2, that there may have been as many as 20 additional flooded locations across the Solent during the 10th March 2008, comprising more than 100 properties in flooded pixels of greater than 0.25 m water depth (although this count reduces substantially using deeper depth filters).

5 Discussion

This work indicated that relatively straightforward boundary condition datasets and analytical tools (GIS, empirical overtopping formulae, LISFLOOD-FP) can allow a regional flood event to be reconstructed; whilst this data collection and validation exercise provide some confidence in future flood modelling results. An extensive and potentially valuable coastal flood event dataset was compiled from ad hoc sources, and used to highlight some of the uncertainties within coastal flood event simulations, including details that could be improved upon in further modelling. For example, the results in Tables 3 and 4 are an indication of uncertainty in the simulated flood outline, and how outputs may be used to determine ‘threatened’ properties (rather than it being known if water actually entered properties), which is potentially useful information to improve the model’s value for further assessment of flood impacts in this region.

Considering the large and varied shoreline in the case-study area, the use of good quality defence and floodplain data was amongst reasons for good model performance (despite minimal calibration). The alternative is to set-up a large coastal numerical model comprising more sophisticated and high-resolution simulations of offshore and nearshore hydrodynamics, coupled to higher spatial resolution floodplain modelling. The improved delineation of flood extents, depths and visualisation of outputs would, however, come at a substantially increased labour and computational cost, but would not necessarily resolve larger uncertainties (e.g. the wave overtopping and breach inputs). However, development and analysis of datasets for this validation case study showed that caution is required for interpretation of model outputs, and continued, systematic collection of flood event data could benefit future calibration efforts.

There is a significant discrepancy between the estimates of the number of properties actually inundated, which highlights a large uncertainty in flood risk analysis, when combining counts of flooded buildings and flood model outputs. For example, if a mean depth–damage curve for UK residential properties (Penning-Rowsell et al. 2003) is applied to the 10th March 2008 flood and no depth cut-off to define which properties flooded is used (i.e. a depth–damage relationship is applied to all properties within the simulated flood outline), this suggests almost £70 million worth of damage could have occurred. Such large impacts are not plausible (e.g. the event would have generated much greater media attention). Instead, counting only the properties flooded to 0.5 m (and then applying the depth–damage information) reduces the regional estimate of property damage to less than £15 million. More detailed knowledge of micro-topography (height of door sills and location of air vents) would obviously benefit the analysis of flood event simulations, as would application of finer grid resolution data. However, despite the value and high quality of LiDAR data for flood inundation mapping, even $\pm$ 0.15 m RMSE in vertical accuracy blurs the sources of uncertainty within flood simulations, for determining shallow flows and whether uncertainty should be attributed to boundary conditions. This issue is complicated by the frequently encountered practical requirements to interpolate grid cells and simplify the representation of floodplain flows, combined with facets such as human responses to events (e.g. sandbagging, and other flood proofing measures).

Priority areas for further work would be numerical studies to improve the spatial understanding of wave and sea-level conditions in the harbours and the upper reaches of tidal rivers, where data recorders and return periods are currently unavailable. The Solent does, however, benefit from a regional coastal monitoring programme which provides publicly available wave and water level recordings of higher resolution and quality than many regions (CCO 2012). The event reconstruction also highlights the potential value of integrating non-coastal flood sources within predictive coastal flood models. For example, storm surge propagation along river channels is more often incorporated within hydrodynamic flood simulations than methods to combine fluvial and coastal sources within modelling scenarios (e.g. determining the impacts of tide locking in the upper reaches of rivers), and the available body of literature in this area is limited. Although we could not obtain flow data for the Solent’s rivers, the 10th March 2008 sea-level event appears to have impacted the upper reaches of some tidal rivers in the region, and this analysis highlights potential limitations for assessing flood consequences in regions when numerical simulations omit fluvial inputs.

The compilation of datasets such as those described in this paper is essential to understand the nature of coastal floods across regions such as the Solent; and similar exercises should be undertaken more frequently and in a systematic manner. The success of this is somewhat dependent upon the collation of datasets as soon as possible following any given event (e.g. much information was lost following the December 1989 English Channel Storm surges and floods). As well as a better baseline understanding of the flood system (e.g. drainage, source–pathway interactions, etc.), ideal datasets of specific relevance for improving future coastal flood event analysis (in addition to those already described) include more accurate mapping of maximum flood extent, and the actual locations of the number of buildings flooded. This would be further complimented by recording flood depths within each building, and ideally data associated with the dynamics and propagation of the flood wave (which would be of particular use for calibrating models which explicitly depict flood hazards such as flow velocities). A substantial upgrade to the methods shown, would be to constrain flood extent and subsequently validate model simulations by the use of remotely sensed data captured during the event (e.g. Schumann et al. 2011), which is increasingly available from both aircraft and satellite platforms. However, the collation of the flood data shown here is sufficient to provide a basic calibration of the model via flooded areas and properties, whilst importantly provides an insightful record of flood defence and human responses which (for this event) are now archived for future use.

6 Conclusions

Collection of flood event data is important to validate coastal flood models, and to understand coastal flood events. The improvised and systematic collation of information shown here has potential to increase the understanding of flood events, and increase the plausibility of inferences made about simulated floods (such as those associated with more extreme storm surge events, or sea-level rise). This kind of monitoring is undertaken to varying degrees elsewhere; for example, the US Federal Emergency Management Agency (FEMA) has a rapid response capacity to document the effects of coastal and inland flood events, which provides an historical perspective on planning decisions and assessment of other events (FEMA 2011). Such data collection exercises provide a useful timeline that can indicate the severity of hazards that can be expected due to a complex combination of factors involved in flooding, such as timing of the event and effects of other sources and pathways. At present, this only happens sporadically in the UK in response to coastal flood events. For example, in Solent, a flood event on 3 November 2005, on the Eastoke peninsula (Hayling Island—Fig. 1) was captured by Havant Borough Council when engineers recorded the flood outline, water depths and properties affected. This was, however, only for a small area and is not routine. In the absence of hard data, other information may prove beneficial; for example, social media can yield a large volume of temporally and spatially referenced photos and observations, as previously noted during floods (e.g. Merchant et al. 2011; Charlwood et al. 2012; Bird et al. 2012).

Sea levels are rising around the UK, and future projections are provided by the UK Climate Impacts Programme (UKCP09) (Lowe et al. 2009). Middle probability estimates for the year 2050 suggest approximately 18–26 cm sea-level rise (SLR) in the south of England (this being the range for low- to high-emission scenarios), which would enable the 10th March 2008 still water levels to become an event with an approximately 1 in 1 year return period probability in most areas of the Solent by 2050. From another perspective, coastal flood simulations described in Wadey et al. (2012) suggest that this SLR scenario would allow an event with the same annual probability as the 10th March 2008 (approximately 1 in 10) to exert at least a fourfold increase in the number of properties likely to experience flood damages by 2050 (assuming existing defences are maintained, but not upgraded).

For many of the Solent locations, most severely affected by flooding during the 10th March 2008 case-study event, defences were significantly upgraded during the 1980s and 1990s; and this continues—of particular note the defences at Selsey are currently undergoing major upgrade (Pearce et al. 2011). However, the water level history and the consequences of the 10th March 2008 event demonstrate that undefended areas remain vulnerable to extreme water levels, whilst areas with good defences are within centimetres of coastal flooding. For areas such as the Solent, where the impacts of coastal flooding can be sensitive to relatively small vertical increases in extreme still water levels, it is essential to collate data from such events to determine the potential effects of more extreme loadings and the impacts of sea-level rise. The use of tools that predict flood impacts will become increasingly important to explore scenarios for adaptation strategies and to improve practical aspects of flood event management, such as flood mapping and the development of technology to allow the integration of flood pathways within forecasting, warnings, and flood event management. This type of dataset may also contribute to improved future management of flood hazards (e.g. verifying or identifying flood hotspots, and information to support new flood defences). Apparent in the reports of flooding during the 10th March 2008 event was that despite the small flood extents (relative to those associated with coastal floods on the UK east and west coasts), the rapid nature of inundation (particularly in some of the undefended areas affected, for example, Yarmouth, Bosham) took communities by surprise. Further, there were some near misses, such as the closeness of the sea level to the top of the docks in Southampton, and reportedly some difficulty closing a flood gate (which prevented substantial flooding) as the tide rose in Portsmouth (BBC 2008b). Documenting events in the manner described in this paper is therefore a valuable exercise to provide context to return period analysis, evidence to support future defence and land-use planning and a form of validation for numerical flood inundation models.

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