



1607 BRISTOL CHANNEL FLOODS: 400-YEAR RETROSPECTIVE

RMS SPECIAL REPORT



Risk Management Solutions

INTRODUCTION

The Bristol Channel Floods of January 30, 1607 caused the largest loss of life from any sudden onset natural catastrophe in the United Kingdom during the past 500 years. Between 500 and 2,000 people drowned in villages and isolated farms on low-lying coastlines around the Bristol Channel and Severn Estuary. The cause of the flood has itself been controversial, in particular following claims in 2002 that the event was in fact a major tsunami. However, evidence of the timing of the floods relative to the tides, other weather observations, and the absence of any reports of an earthquake, support the theory that the event was a wind driven storm surge superimposed on an extreme spring tide.

The event remains the most catastrophic flood in western Britain, only rivaled by storm surge floods like those in 1570 and 1953 along the east coast of the United Kingdom. While the sea defenses that line the Bristol Channel have been raised since 1607 (many of which dated back to Roman times), if the excess sea levels experienced in the event occurred today, the consequences would be catastrophic. As the 400th anniversary of the Bristol Channel Floods occurs, this report reflects on the historic event, examines recent research into the causes of the flooding, and analyzes the implications if the event were to recur in 2007.



Figure 1: Map of the United Kingdom with magnified view of the Bristol Channel and the Severn Estuary

THE 1607 BRISTOL CHANNEL FLOODS

The 1607 floods occurred just at the emergence of widespread literacy in England, but before the scientific revolution of the mid-17th century. The year 1607 marked the date of the first permanent English settlement at Jamestown in America, and a number of ships sailing to the New World were held up by stormy weather during the month of January. Shakespeare was still writing and performing and the King James Bible began to be translated and edited. The language of the King James Bible is exactly contemporary with the descriptions of the flood; the style in which the flooding is described is vernacular, freeform and eloquent:

“...let us fix our eyes upon these late swellings of the outrageous Waters, which of late now hapned in divers partes of the Realme, together with the overflowing of the Seas in divers and sundry places thereof: whole fruitful valleys, being now everwhelmed and drowned with these most unfortunate and unseasonable salt waters.” “Many men that were rich in the morning when they rose out of their beds, were made poore before noone the same day.”

DOCUMENTATION

As there were no newspapers at the time, principal accounts reporting the impact of the flood survive in a small number of pamphlets privately printed in London. These original pamphlets (which were reproduced over the years), with titles like *Lamentable Newes out of Monmouthshire* and *Newes of out Summerset-shire*, were sold by printers who also published Shakespeare, operating out of the churchyard of St Paul’s in London. Stories emphasized miraculous escape and all reports were presented within a religious context, using the event to sermonize for an improvement in morality among the people. One pamphlet entitled *Gods warning to his people of England* begins with “MANY are the dombe warnings of Distruction, which the Almighty God hath lately scourged this our Kingdome with; And many more are the threatning Tokens, of his heavy wrath extended toward us.” The religious wrapping very often seems to have been a cover for the presentation of straight news.



Figure 2: Depiction of flooding as shown in the pamphlet *Lamentable Newes out of Monmouthshire* (from *Great Flood of 1607* website: <http://website.lineone.net/~mike.kohnstamm/flood/>)

Beyond the pamphlets, information on the flooding is supplemented by parish records, including inscriptions on churches and accounts from a small number of contemporary historians and writers. The most detailed information for a single town is found in the *Lost Chronicle of Barnstaple* as compiled by Dr. Todd Gray of Exeter University in 1998 from records written between 1586 and 1611 by the Barnstaple town clerk, Adam Wyatt (Gray, 1998).



Figure 3: Stone on the wall of a local church in Peterstone Wentlooge (northeast of Cardiff) marking the height reached by the 1607 Bristol Channel Floods (about 1.9 meters¹ above ground level) and reading "The Great Flood Jan 20, 1606" (from Great Flood of 1607 website: <http://website.lineone.net/~mike.kohnstamm/flood/>)

DATE OF OCCURRENCE

While there is agreement among the historical records that the event took place around 9:00 am local time, there has been some confusion on the date of the Bristol Channel Floods, which has led to the event being duplicated in historical catalogues. Dates of January 20 or January 30 are listed, as are years of 1606 or 1607. This confusion lies in the use of the Julian or Gregorian calendars.

At the time of the flood, the actual date was Tuesday, January 20 but as a result of the shift from the Julian to the Gregorian calendar, it is now recognized that the correct modern date is January 30. By the mid-16th century it had become recognized that the dates of the religious festivals of Easter and Christmas were drifting relative to the solar year because of the overcompensation of the four year leap year cycle in the Julian calendar. Pope Gregory XIII published a decree on February 24, 1582 authorizing both the compensatory removal of selected leap years and a one time correction of the calendar to take out ten days so that October 15 followed October 4 in 1582. However, the idea of following any decree from Rome was so unpalatable in England that it took until 1752 to make the adjustment.

¹ Systeme Internationale (SI) or Metric units, the internationally accepted standard for scientific measurement, are used for modelling and throughout this report – however, indirect quotes of figures given in original sources in Imperial units, are given here in both Imperial and Metric units. Direct quotes in imperial units are unaltered.

The confusion over the year of 1606 or 1607 lies in calendar usage as well. The beginning of a calendar year in medieval England as based on the Julian calendar was taken to start on the incarnation of Jesus or nine months before Christmas on December 25. Therefore, the month of January remained within the previous year (i.e., 1606), and a number of contemporary inscriptions in village churches around the Bristol Channel memorialize the flood this way (as seen in Figure 3). However, there had been a general move in Europe to follow the Gregorian calendar in the 16th century, wherein January 1 was the start of a new year and by 1607 this was becoming the accepted norm in London. Therefore, the more ‘modern’ people in London who documented the floods had 1607 as the year of occurrence.

GEOGRAPHICAL EXTENT AND IMPACT OF FLOODING

Flooding is known to have extended along more than 400 km of the northern and southern coasts of the Bristol Channel and up the Severn Estuary as far as Gloucester (see Figure 4 for impacted towns and cities and Figure 5 for county boundaries and relative elevations). The 1607 floods seriously affected four separate areas around the Bristol Channel, and summary accounts of the extent of the flooding exist for all these areas except the coast of southwest Wales. As there was no census before 1607, the population living in the flooded areas or drowned in the flood cannot be known. The pamphlet *Lamentable Newes out of Monmouthshire* states the number drowned was “not known to exceed 2000.” In a small number of parishes, the number has been tabulated suggesting that the total drowned in the event was probably somewhere between 500 and 1,000.



Figure 4: Map of Bristol Channel and Severn Estuary showing major cities around the channel, as well as the rivers Avon and Severn and the Somerset Levels

The southwestern extent of known flooding was at the town of Barnstaple in north Devon “where the low Marshes and fenny groundes... were overflowne.” In detailed accounts, it is reported that three people were killed and £2,000 worth of goods were lost. In Barnstaple, the height of the flooding was 6.15 ± 0.25 m above Ordnance Datum (AOD), as recently reconstructed from detailed accounts of the streets and quayside locations that were flooded in 1607 (Haslett and Bryant, 2004). Flooding also extended along the coast of southern Wales in the outer Bristol Channel into Swansea, over Laugherne and Llanstephan in Carmarthenshire and was said to have extended into Cardiganshire, although there are no detailed accounts from this area. These were two of the four separate areas flooded during the 1607 flooding.

Passing eastwards from Barnstaple, the coastline is steep until the town of Minehead. Beyond Minehead lies the low-lying Somerset Levels, a wetland area of central Somerset approximately 650 km² in area, and even farther eastward is the town of Bristol. This entire region – including up to the city of Gloucester – was the third area to be flooded. Almost the whole of the Somerset Levels was inundated during the 1607 event, including “all Brent-Marsh the Sea swelled up as hye as Bridgewater.” Numerous towns and villages within the wetland area were drowned, including the market town of Hunsfelde (modern-day Huntspill) along with the villages of Grantham, Kenhouse and Kingson (modern-day Kingston Seymour). At Kingston Seymour, the water reached 7.74 m AOD. Many men, women and children were said to have been drowned in the county of Somerset as well. Water passed up the River Avon into the city of Bristol, where many cellars and warehouses filled with merchandise were spoiled and “people of the Towne were inforced to be carried in Boates, by and downe the said Cittie about their busines in the Fayre time there.”



Figure 5: Map of Bristol Channel and Severn Estuary showing county boundaries and relative elevations

All of the low-lying land on both the sides of the River Severn from Bristol to Gloucester was overflowed, and almost all of the bridges on the tributaries of the river between these cities were destroyed. At the village of Almondsbury a few kilometers inland, an account was written by the Vicar John Paul which said that "...in Saltmarsh many howses overthrowne. In Hobbes house syx foote hyghe. In Ellenhurst at Wades howse the sea rose neere 7 foote and in some howses there yt ran yn at one wyndow and out at an other." On the Welsh side of the River Severn at Chepstow, two people drowned, while the parish register at Arlingham recorded that about twenty people were killed.

The fourth area to be flooded was an extensive area of inundation in the Gwent lowlands. The area measured 39 km in length and 6.5 km in width, with water depths of 2 m or more. These flood plains protected by flood defenses are generally at an elevation of 5 to 6 m AOD. Height of the water levels recorded by marks in the church at Goldcliff, Newport in the Gwent lowlands surveyed by Boon (1980) was 7.14 m AOD (i.e., about a 1.5 m water depth at the location).

In some parts of the flood plain the population at the time was probably higher than it is today, as the fertile area was being grazed by large populations of cattle and sheep. *Lamentable Newes out of Monmouthshire* describes the submersion of 26 parishes in this region: "Matharne, Gouldenlifte, Portescue, Nashe, Caldicot, Saint Pere, Vndye, Lanckstone, Roggiet, Wiston, Lanihangiell, Lanwerne, Iston (Ofton), Christchurch, Magor, Milton, Redwicke, Bashallecke, Saint Brides, Roney, Peterston, Marshfield, Lambeth, Wilfricke and Saint Mellins." Flooding also extended into Newport, Cardiff and Cowbridge. In Cardiff, the Church of St. Mary was undermined and destroyed alongside the River Taff. In total, the damage was estimated as above £100,000, with the land overflowed in Monmouthshire valued at £40,000 a year. An estimated 500 were drowned in this area along with many thousands of cattle.

It should be noted that an entirely separate area of flooding occurred on the evening of January 30, 1607 on the east coast of England in the county of Norfolk, not far from Kings Lynn at the eastern end of the Wash, in a place called March-land. The water was said to have broken out of an old breach and in a quarter of an hour, overflowed the Marsh. A few people drowned and a number of houses were "wading up to the middles in Water, joyning with land Waters that fell from the high groundes."

CAUSE OF FLOODING

There are many lines of evidence that support the 1607 Bristol Channel Floods as being a wind driven storm surge superimposed on an extreme spring tide. However, one of the principal interests in this event is that it has been interpreted as a potential tsunami rather than a storm surge flood. This reached its highest point in the aftermath of the 2004 Indian Ocean tsunami (see RMS, 2004). Articles appeared in the press and the BBC aired a program in the spring of 2005 exploring the tsunami theory postulated by Bryant and Haslett (2002). Even public notices located on the coast of Gwent in southern Wales, commemorating the flood, promote the tsunami explanation.

While there are some descriptions of the arriving flood that have elements comparable to a tsunami, there are many other descriptions that discount the tsunami explanation and these are considered here, including the state of the tides and the weather in 1607. In the ten surviving accounts of the flood, there is only one that suggests a tsunami and this account is also, perhaps not coincidentally, the account which contains the greatest religiosity in style and content. From the pamphlet *Gods warning to his people of England*:

“Then they might see & perceive a far of as it were in the Element, huge and mighty Hilles of water, tumbling one over another, in such sort as if the greatest mountaines in the world, has over-whelmed the lowe Valeys or Earthy grounds. Sometimes it so dazled the eyes of many of the Spectators, that they immagined it had bin some fogge or miste, comming with great swiftnes towards them: and with such a smoke, as if Mountaynes were all on fire: and to the view of some, it seemed as if Myliyons of thousandes of Arrowes had bin shot forth at one time, which came in such swiftnes, as it was verily thought, that the fowles of the ayre could scarcely fly so fast, such was the threatning furyes thereof.”

While this description does evoke visions of an advancing tsunami along the coast of Thailand, seen in brilliant sunshine on December 26, 2004, there is little evidence to support that the tsunami was generated by an offshore earthquake, which is the most likely culprit for generation (rather than a landslide or volcanic eruption). Before considering other lines of evidence around the cause of the flood (high spring tide along with stormy weather conditions), it is worth weighing up the evidence that this could be an earthquake-induced tsunami.

AN EARTHQUAKE-INDUCED TSUNAMI

Over the past 500 years, the largest earthquake to have occurred in the region around the British Isles had a surface wave magnitude (M_s) of 5.5. This earthquake occurred in 1931 in the middle of the North Sea. As the attenuation of ground motion is very slow in northwestern Europe, the earthquake was felt strongly in all of the countries that ring the North Sea and caused minor damage along the east coast of England from Yorkshire to Norfolk. The earthquake, however, was still far too small to have generated a tsunami.

Typical tsunamigenic earthquakes are common along major subduction zone boundaries and start at around magnitude 7 (i.e., releasing around 40 times more energy than the largest earthquake known in this region). In order to generate a 3 to 4 m tsunami at a distance of several hundred kilometers as implied by the tsunami explanation, an earthquake of magnitude of 7.5 or higher (i.e., around 200 times more energy than the largest known earthquake in northwestern Europe) would have occurred. An earthquake of magnitude 6 or higher anywhere along the Atlantic margin of Ireland in 1607 would have been felt and reported across the whole of northwestern Europe, including Ireland, Great Britain, and France.

There was no such earthquake at the time of the 1607 Bristol Channel Floods. There is also no record of a tsunami in 1607 along any of the other coasts in the region from the Isles of Scilly to Cornwall to Brittany to southern Ireland. This evidence is consistent with the 1607 Bristol Channel Floods being a storm surge focused up the Severn Estuary. Furthermore, in 1755, a magnitude 8.5 earthquake was felt across the whole of southwestern Europe, occurring along the plate boundary to the southwest of Portugal. It caused catastrophic damage in towns throughout the southern half of Portugal and seiching in lakes throughout Great Britain and Scandinavia. It was a major regional tsunami comparable to that of the 2004 Indian Ocean tsunami of December 26, 2004. Although it was not recorded in the Bristol Channel, it was noticed (at low tide) in Cornwall.

AN EXTREME SPRING TIDE

It was acknowledged that at the time the flood hit in 1607 an extreme spring tide was to be expected. As recorded by the Vicar of Almondsbury John Paul: “The ryver of Severn rose upon a sodeyn Tuesday mornynge the 20 of January beyng the full pryme day and hyghest tyde after the change of the moone.” A number of other accounts also suggest that rivers were full. In the pamphlet *Lamentable Newes out of Monmouthshire*, it was written that “The Sea being very tempestuously moved by the windes, overflowed his ordinary Bankes.”

There was little doubt among the local people as to the cause of the flood. Poet John Stradling was caught at the Severn crossing at Aust near Bristol by the flood and writing a poem about the event to his friend Thomas Luttrell of Dunster, he noted: “If you crave to understand the Severn’s unwonted floods, what causes they have, and the source of this madness, the common people attribute it to the moon and the driving winds, they rise their mind no higher.”

Horsburgh and Horritt (2006) have calculated the tides expected for January 1607 based on the known periodicities of the astronomical forces (Figure 6). In Avonmouth at the mouth of the River Avon (near Bristol), the highest tide in the month of January 1607 was 7.86 m AOD occurring on January 30 at 9:00 am local time. As Horsburgh and Horritt explain, this tide is exceptional not just for the month but due to the semi-diurnal tidal forces being at their most extreme (i.e., when the sun and moon are both overhead at the equator and the moon is closest to the Earth). As the conditions required to have an extreme semi-diurnal tidal force are estimated to occur approximately every 4.5 years, the next one is expected on March 20, 2007 (Pugh, 1987). At Avonmouth, the maximum elevation is calculated to be 7.78 m AOD, 8 cm lower than was modeled for January 30, 1607.

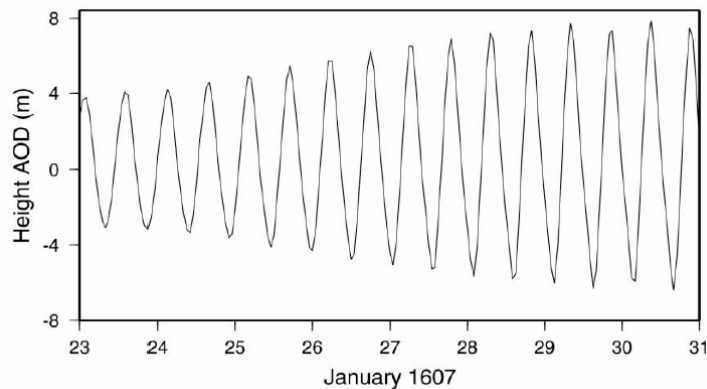


Figure 6: Tidal curve for Avonmouth for January 23-31, 1607 (from Horsburgh and Horritt, 2006)

WEATHER CONDITIONS

As with historical notes about the extreme spring tide in January of 1607, there are also notes from the historical record that indicate a windstorm occurred. In William Camden's 1607 edition of *Britannia*, he notes that a storm had been continuing for some time: "After a Spring-tide, being driven back by a Southwest-wind (which continued for 3 days without intermission) and then again repuls'd by a very forcible Sea-wind, it raged with such a tide." In addition, the Barnstaple parish register recorded that the specific windstorm had begun in the middle of the night: "This storme begane at 3 of clock in the morning and continue tyll 12 of clock of the same day."

Only one account – in the pamphlet *Gods warning to his people of England* – omits any mention of a windstorm, and simply states "about nine of the clocke in the morning, the Sunne being most fayrely and brightly spred." There is no mention of rain with the storm and there is evidence that at the time the flood hit, the sky was clear and the early winter morning sun was shining brightly out of the southeast.

This is typical of one class of rapidly intensifying extra tropical cyclones that has gathered a 'dry sector intrusion' as a result of very cold dry air from above the tropopause gaining entry into the heart of the storm. A clear sky at the heart of a storm has been a feature of a number of the most recent windstorms in northwestern Europe, including Windstorm Lothar which hit Paris on December 26, 1999. It is even possible that the 1607 windstorm was itself associated with a sting jet, bringing extreme wind speeds across the Bristol Channel, although no accounts indicate wind damage from the storm and therefore wind speeds were probably not as high as 30 m/s over land.

If one rereads the account from *Gods warning to his people of England* that appears to support the idea that this was a tsunami, it reports enormous waves with a very strong wind blowing across their breaking crests, all seen in bright sunshine. The waves would have been far higher than normal because higher water depths over the mudflats along the edge of the Severn Estuary would lead to higher waves. Additionally, the view reported was probably from the hills along the east Somerset coast, with the sun behind the observer.

It is also possible that the waves were being observed coming through the sea defenses. The pamphlet *Newes out of Summerset-shire* reports breaching: “The sea at a flowing water meeting with Land-floudes, strove so violently together, that bearing downe all thinges yt were builded to withstand and hinder the force of them, the bankes were eaten through and a rupture made into Somerset-shire. No sooner was this furious invader entred, but he got up hie into the Land, and encountring with the river Severn, they both boild in such pride that many Miles, [to the quantity of 20 in length, and 4 or 5 at least in bredth] were in a short time swalowd up in this torrent. This Inundation began in the morning, & within few houres after, covered the face of ye earth thereabouts [that lay within the distance before named] to the depths of 11 or 12 foot in some places, in others more.”

The same account that appears to suggest a tsunami nevertheless also indicates that the flooding took far longer than would have been consistent with this explanation. In *Gods warning to his people of England*, it notes: “But so violent and swift were the outrageous waves, that pursued one an other, with such vehemencie, and the Waters multiplying so much in so short a time, that in lesse then five houres space, most part of those countreys (and especially the places which lay lowe,) were all overflowen.” From this description, one is reminded of the city of New Orleans filling with water in 2005 after the storm surge from Hurricane Katrina had receded.

Some other indications of the synoptic meteorology of the event can also be traced from the historical accounts. After the height of the flood, later in the morning towards the end of the storm, it was reported that in the County of Glamorgan (towards the western end of the area flooded), a blind man washed out of his house in his bed, caught hold of a rafter of a house “swimming by the fiercenesse of the Windes, then blowing Easternely.” He was driven safely to land and so escaped. This suggests that the center of the storm had passed and he was now on the northern side of the storm center. An easterly wind following the storm is also suggested by an account by the Vicar of Almondsbury, John Paul, who said at Bristol “the mornyng tyde was hygher than that Evenyng tyde by nyne foote of water,” a greater difference than could be explained by the surge alone. This implies a negative storm surge associated with an easterly wind by the evening, as expected differences seen in the diurnal tide is most often less than 0.5 m.

Finally, the flooding close to Kings Lynn in Norfolk, the lone section of the east coast of Great Britain affected by the flooding, suggests that there was a strong northeast onshore wind at the same time as the extreme tide. This must have been on the north side of the center of an extra tropical cyclone. The last time that Kings Lynn was flooded on its own was on January 11, 1978 when a slow-moving low pressure system was located to the southeast of a major anticyclone, creating a very strong pressure gradient and northeasterly winds on its northern side.

THE 1607 EVENT IN 2007

For the 400th anniversary of the Bristol Channel Floods, RMS evaluated the potential impacts to the region of a storm surge superimposed on an extreme spring tide comparable to that known to have occurred on the morning of January 30, 1607. For the purposes of this reconstruction, it is important to consider how the height reached by the tide itself has changed over the past four centuries.

CHANGES IN TIDE LEVELS SINCE 1607

A number of observations of the Bristol Channel Floods constrain how much sea level change has occurred since 1607. At Barnstaple in the outer Bristol Channel, the town clerk, Adam Wyatt, noted that the water level reached 5 to 6 feet (1.5 to 1.8 m) higher than “ever it was seen by any now living.” If one assumes at a minimum that the previous highest water experienced at this location reflected an earlier extreme spring tide without any associated supplementary surge, then this tide only reached an elevation of 4.35 to 4.65 m AOD (e.g., 6.15 m minus 1.5 to 1.8 m). However, the predicted high tide at 7:40 am on January 30, 1607 is 5.7 m AOD (Haslett and Bryant, 2004), which is only 0.45 m below the average height observed in the 1607 flood in the town. The difference relative to the 1.5 to 1.8 m height excess over the previous highest known water implies at least a 1 m rise in maximum high tide levels at this location over the past 400 years. The southwest peninsula of the U.K. is known to be sinking as a result of loading of the continental shelf and postglacial rebound, with estimates of somewhere between 1 to 2 mm/yr. Superimposed on this is a rise in eustatic (i.e., global) sea levels of around 2 mm/yr for the past century. However, these two causes combined do not appear to add up to the change in high tide levels over the past 400 years (Figure 7). Other factors could also be relevant, including the shrinkage of peaty soils as a result of extensive drainage since 1607, leading to the subsidence of key churches with flood marks.

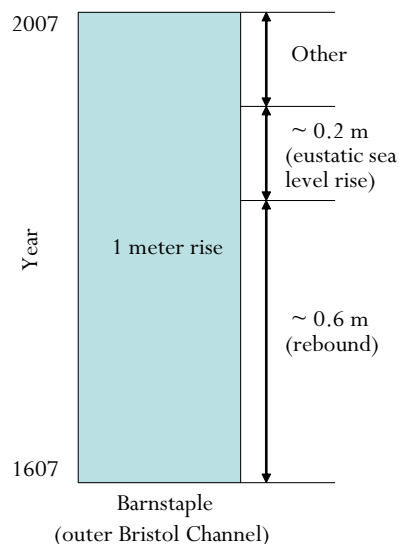


Figure 7: Schematic showing 1 meter rise in high tide levels at Barnstaple over the past 400 years due to postglacial rebound, global sea level rise and other conditions

As previously noted, at Avonmouth near Bristol in the inner Bristol Channel, the predicted tide on the morning of January 30, 1607 was 7.86 m AOD. This value is close in measurement to the flood height of 7.74 m, as marked at Kingston Seymour church not far away (although 2 to 3 km inland). In addition, the evening tide on January 30, 1607 was 9 feet (2.7 m) lower than the morning tide, as reported by the Vicar of Almondsbury, John Paul. One feature of the most extreme spring tides is they achieve some of their extra height as a result of diurnality (i.e., the difference in height between the two tides on the same day). However, the difference from diurnality in the Bristol Channel probably only contributes 0.5 m of the total difference. The remainder is due to storm surge effects, including some contribution from a negative storm surge in the evening (i.e., wind blowing to the east).

As it is not possible to separate all these factors, conservatively and with reference to the known height of the surge in Barnstaple, it is appropriate to consider that the surge contributed at least 1.5 m – and maybe as much as 2 m – to the water height experienced in the morning. If it was 1.5 m, this implies that extreme high tide levels have risen by about this much since 1607. Again, it appears that less than half of this could be explained by isostatic and eustatic sea level changes, implying, as in Barnstaple, the possibility that the tidal range has increased over the past four centuries. Such an increase does not appear to have been previously identified, but could reflect reductions in tidal friction in the Severn Estuary and the construction of flood defenses preventing the spillover tidal flooding of salt marshes – in particular in the Somerset Levels, removing the peak from the highest tides of 1607.

CHOICE OF MODELED FLOOD WATER DEPTHS

The changes in sea levels and high water levels require that in reconstructing the combination of surge and tide in 2007, the water level would reach higher levels above ordnance datum (AOD) than is indicated by the heights actually marked on churches in 1607. This difference appears at least 1 m in excess of the water levels actually reached in the outer Bristol Channel and potentially as much as 1.5 m in the inner Bristol Channel. As the exact mix of surge and tide is not known for 1607, a range of flood heights has been employed for estimating the losses in 2007.

In the outer Bristol Channel water levels have been taken to be between 0.85 m and 1.35 m higher than observed in Barnstaple (i.e., 7 m and 7.5 m) and the same water levels have also been applied on the southwestern coast of Wales. In the inner Bristol Channel, surge heights of 8.5 m and 9 m have been selected, corresponding to 1.3 to 1.9 m higher than the elevations of the flood heights marked on the churches in the region. Horsburgh and Horritt (2006) have also shown that it is possible to have a surge and extreme tide event giving water levels of 9.44 m at Goldcliff and at least 9.02 m at Kingston Seymour. Therefore, a further extreme water level has been explored in the inner Bristol Channel reaching 9.5 m above Ordnance Datum (AOD).

STORM SURGE HEIGHTS

Based on these water levels, the surge flood was ‘bathtubbed’ at constant elevation across all the flood plains surrounding the Bristol Channel, although, as explained, with different maximum elevations for the inner and outer Bristol Channel. Although bathtubbing – simply filling up the basin to the height of a specific contour – will overestimate floodwater heights in the Somerset Levels, where the area below the flood elevation extends more than 20 km inland, the total value of buildings is relatively limited in the areas that are most sensitive to this approximation. In terms of these reconstructions, the 9 m and 9.5 m flood elevations would almost certainly overwhelm the defenses located around the inner Bristol Channel, while the 8.5 m flood elevation (with a return period of 100 years at Newport) is an event that might be contained by the flood defenses at some locations. As reported on January 30, 1607 the significant wave action superimposed on the surge increased the potential for even relatively well-built defenses to be overtopped and to fail. Therefore, while the losses reconstructed for the 9 m and 9.5 m elevations in the inner Bristol Channel are unlikely to be affected by the defenses currently in place, there is a legitimate argument that some (potentially a significant) proportion of a flood reaching only 8.5 m would be prevented from inland inundation by the defenses.

For this reconstruction, the flood surface was superimposed over a 50 m by 50 m resolution grid to determine reference flood depths to be used in loss calculations. For example, Figure 8 shows the extent of the flood surface for an 8 m water level in the outer Bristol Channel and a 9.5 m water level in the inner Bristol Channel.

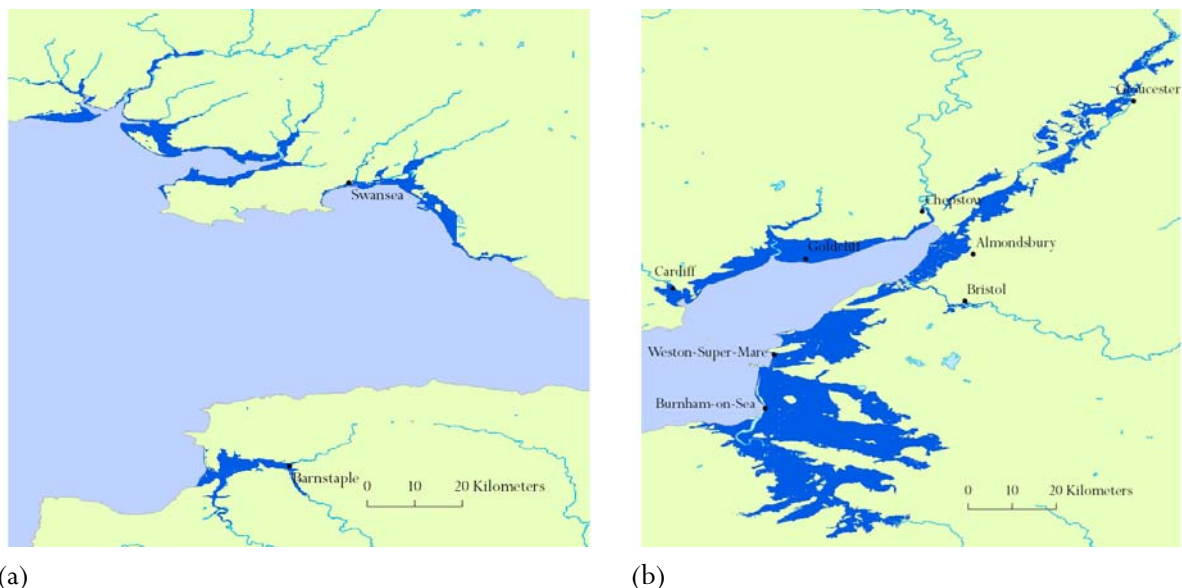


Figure 8: Maps of Bristol Channel showing extent of flooding as modelled in 2007: (a) in the outer Bristol Channel (8 m water level) and (b) in the inner Bristol Channel (9.5 m water level)

EXPOSURE

RMS estimates the insured value of the building inventory in Great Britain, including structures and their contents, at nearly £8 trillion (US\$15.5 trillion) for residential, commercial, industrial, and agricultural properties, the majority of which can be categorized as residential. This estimate is based on combining economic data published by the British government summarizing the value of gross fixed capital assets for various categories of property, with estimates of insurance take-up rates. RMS used the standard economic technique known as the Perpetual Inventory Method (PIM) as described in the OECD manual *Measuring Capital* (OECD, 2001) to extrapolate the country-wide total value of assets at risk from available 2003 vintage data to July 2006. The insured values were then taken down to a 50 m resolution grid using a combination of many data sources including data from the 2001 U.K. census, data published by the government concerning the location of commercial properties, and remote sensing data.

The area affected by this event includes several urban regions including parts of Bristol, Cardiff, Swansea, the north Avon coast, and Gloucester. RMS estimates that the total insured value of property affected by this event is nearly £32 billion (US\$63 billion) or approximately 0.4% of the total exposure across the United Kingdom.

BUILDING AND CONTENTS VULNERABILITY

The vulnerability of the building and contents exposures is a function of the flood depth. The methodology utilized in this reconstruction takes the flood depth in each grid cell, and uses it to estimate the mean damage and uncertainty in damage (e.g., standard deviation) of the exposures within that cell. Each grid cell has been assigned an 'inventory region' which describes the typical mix of specific building types within it based on the occupancy (i.e., residential, commercial, industrial or agricultural), as well as other factors including a building's age and height.

Several factors are critical in determining the vulnerability of a property or group of properties. One of the most important factors is a building's height. For example, taller buildings tend to have more restricted contents damage than shorter buildings, as part of the insured contents will be located on the higher floors that are not flooded.

INSURED LOSS ESTIMATES

Based on the assumptions outlined here, the likely range of insured loss to the residential, commercial, industrial, and agricultural properties is between £7 billion and £13 billion, of which roughly 50% to 60% is attributed to buildings losses and the remaining attributable to contents losses (Table 1). As seen in Table 1, scenario 3 represents a set of 'most likely' possible flood heights so that the best estimate of loss from this event is £9 billion. These figures do not include losses to other types of insured property, such as automobiles and forests.

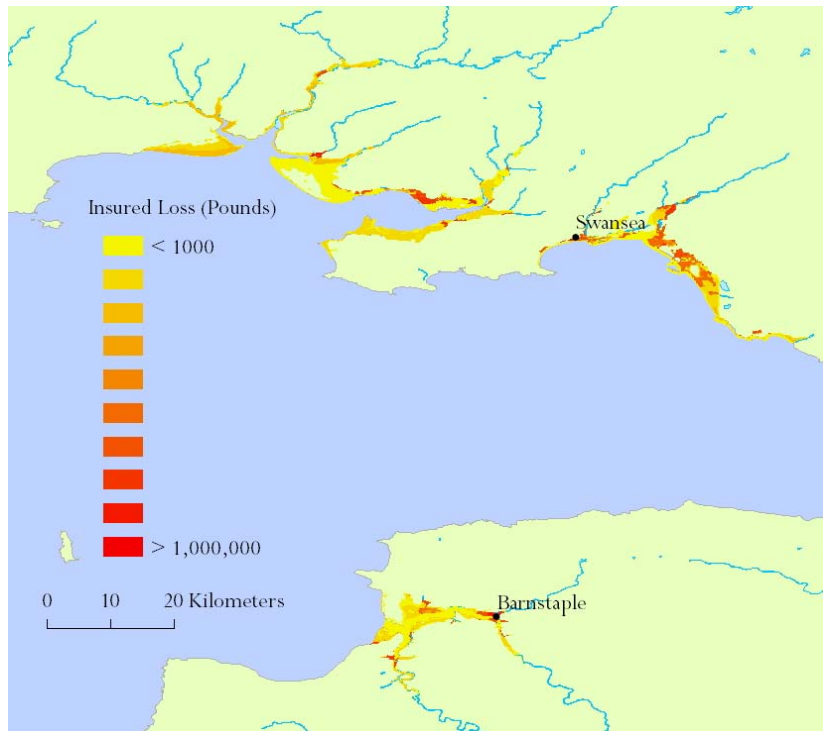
This wide range in estimated loss arises primarily from the fragmentary nature of the historical record, as a range of assumptions on the extent of flooding was necessary in order to consider a reconstruction of the 1607 event. Additionally, there is inherent uncertainty in the vulnerability of the building and its contents to the severity of the flooding.

Table 1. Total losses by insured coverage for five flooding scenarios (scenario 3 is ‘most likely’)

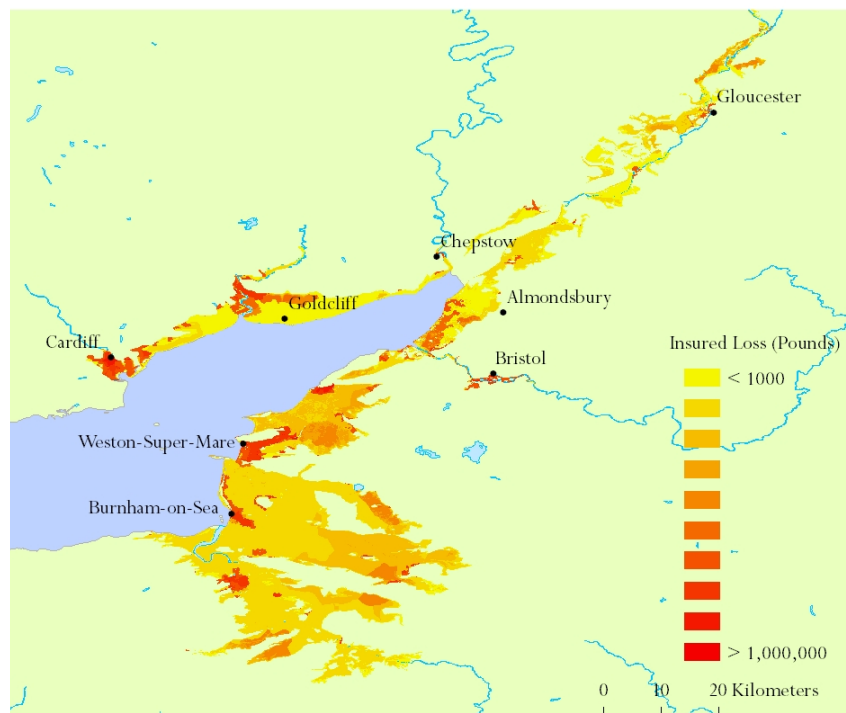
	Water Height Above Ordnance Datum (m)		Total Losses by Insurance Coverage (billions of pounds)		
	Outer Bristol Channel	Inner Bristol Channel	Building	Contents	Total
Scenario 1	8.0	9.5	7.5	5.5	13.0
Scenario 2	7.5	9.0	5.5	5.5	11.0
Scenario 3	7.0	8.5	5.0	4.0	9.0
Scenario 4	6.5	8.0	4.5	3.5	8.0
Scenario 5	6.0	7.5	4.0	3.0	7.0

Over 80% of the loss occurs in the inner Bristol Channel, which incurs worse flooding and also includes dense urban exposure in the cities of Bristol, Cardiff and Gloucester (Figure 9(b)) with the remaining loss in the outer Bristol Channel along the southwestern coast of Wales and near Barnstaple in Devon (Figure 9(a)). About 30% of the loss is attributed to rural locations. It should be noted that these figures represent the most likely range of loss but do not take into account many of the issues that are known to impact the total insured loss from a major catastrophe such as this.

Some unmodeled factors serve to mitigate the loss, such as the action of sea defenses or the conservation of sea-water volumes. Other factors, many of which are explicitly calculated by the RMS U.K. storm surge model, will serve to inflate the loss, such as additional coverages (e.g., business interruption) or post event loss amplification. Loss amplification models effects that have been observed in past disasters such as Hurricane Katrina in 2005 and includes claims inflation, economic demand surge, and repair-cost delay. While these factors are not considered for this reconstruction, they will be available for analysis in the future as RMS expands its U.K. storm surge model (that currently covers the east coast of the U.K.) to cover the southern and western coasts.



(a)



(b)

Figure 9: Maps of insured loss estimates (a) in the outer Bristol Channel (assuming 8 m water level) and (b) in the inner Bristol Channel (assuming a 9.5 m water level)

THIS EVENT IN PERSPECTIVE

The most notorious storm surge catastrophe in the 20th century in the U.K. occurred on January 31, 1953, killing over 2,000 people in Europe and resulting in unprecedented property damage along the North Sea coast in the United Kingdom. In 2003, RMS estimated that a repeat of this event in terms of the areas flooded would cause insured losses in the U.K. totaling £5.5 billion. Given recent levels of development in the affected areas this translates to as much as £7 billion in 2007 values. Interestingly, this figure is superseded by several of the loss estimates from the 1607 flood reconstruction presented here, highlighting the risk from severe flooding in the west of the country.

The probability of a repeat of the 1607 Bristol Channel Floods is, however, very small. Recent work on water level extremes for the inner Bristol Channel along the Severn Estuary suggests that the combination of an extreme tide with an extreme surge is itself very unlikely. The 50-year return period water level currently modeled for Avonmouth is 8.69 m while at Newport it is 8.43 m (Blackman, 1985). As extreme water levels rise only slowly with return period, the 8.5 m level is the 100-year event at Newport while the 1,000-year return period is only 8.76 m. The best reconstruction of the 1607 flood, including the increases in high tide levels, would probably be between the 8.5 m and 9 m elevations, reflecting an event with a return period in the range of 500 to 1,000 years, consistent with it being the most catastrophic event known from this region, probably over at least 500 years (and potentially longer).

However in reference to previous studies of extreme water levels, it is salutary to consider the implications of the storm surge from Windstorm Martin on December 27, 1999 in the Gironde estuary in southwestern France. At the Blayais nuclear power plant on the Gironde, home of four reactors, the storm surge reached one meter higher than had been considered the maximum possible water level at the facility. As a result, the water overtopped the defenses and flooded several meters of the lower level of the facility. Without any internal flood protection system, the water spread over a large network of galleries, damaging pumps and electrical circuits. Although little has been published about what actually transpired through the night of the storm, it is acknowledged that as a result of circuit failures, as well as to the interruption of the external power lines, the four reactors were progressively shut down between 9:00 pm local time on December 27 and 12:30 am local time on December 28.

On January 5, 2000, the French Nuclear Safety Authority admitted that there had been a Level 2 Emergency at the site. Although not confirmed, there were rumors that three out of the four primary cooling pumps were lost as a result of short circuits during the surge, and that the operators of the reactors had sent messages to the authorities warning of the potential for an impending catastrophe. On the Bristol Channel, the reactors at Hinkley Point and at Oldbury are also vulnerable to being flooded by extreme water levels higher than anticipated in the design of the facilities. Where accompanied by an intense windstorm, the operations and even safety of these facilities could potentially be significantly challenged by the repeat of a surge with tide event comparable to 1607.

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