ONR Expert Panel on Natural Hazards

NS-TAST-GD-013 Annex 3 Reference Paper:

Analysis of Coastal Flood Hazards for Nuclear Sites

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Sub-Panel on Meteorological & Coastal Flood Hazards

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LIST OF ABBREVIATIONS[1]

AR4	Fourth IPCC Assessment Report
AR5	Fifth IPCC Assessment Report
ASMITA	Aggregated Scale Morphological Interaction between Inlets and Adjacent Coast Model
CCO	Channel Coastal Observatory
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CFD	Computational Fluid Dynamics
Defra	Department for Environment, Food and Rural Affairs
DEM	Digital Elevation Model
EA	Environment Agency
GIA	Glacial Isostatic Adjustment
GPD	Generalised Pareto Distribution
H++	Plausible high-end climate change scenarios, typically more extreme climate change scenarios on the margins or outside of the 10th to 90th percentile range presented in the UKCP09 projections
IPCC	Intergovernmental Panel on Climate Change
JPM	Joint Probability Method
LiDAR	Light Detection and Ranging.
M	Moment magnitude
MCCIP	Marine Climate Change Impacts Partnership
MHWL	Mean High Water Level
MLWL	Mean Low Water Level
MSL	Mean Sea Level
NAO	North Atlantic Oscillation
NERC	Natural Environment Research Council
ONR	Office for Nuclear Regulation
RCP	Representative Concentration Pathway
RP	Return Period
SCAPE	Soft Cliff and Platform Erosion model
SSJPM	Skew Surge Joint Probability Method
TAG	Technical Assessment Guide
UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018

[1] A number of additional numerical model packages are described in Section 7. Their names and functions are fully explained therein and for further detail please refer to Lawless et al. (2016).

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1 INTRODUCTION

1. A key element of developing a safety case for nuclear plant at a nuclear licensed site is the demonstration that the plant is adequately protected against external hazards, including those related to meteorological and geological processes. An indispensable component of this process is the characterisation and quantification of the external hazards that can credibly challenge nuclear safety at the site. Guidance for Inspectors on the assessment of site-specific studies to quantify the threat from external hazards at nuclear sites is provided in *Nuclear Safety Technical Assessment Guide NS-TAST-GD-013* (ONR, 2018a), generally referred to as TAG 13.

2. Annex 3 of TAG 13 (ONR, 2018b) is focused specifically on the hazards of coastal flooding, coastal erosion and tsunami and their analysis for nuclear sites in the UK. The purpose of this document is to provide additional detail on the analysis of tsunami and coastal flooding and erosion hazards. The present document is intended to provide guidance to inspectors as well as experts or consultants called upon to assist Inspectors with assessments of tsunami and coastal flooding hazard studies for nuclear sites in the UK. It also builds upon the overview of climate change provided in Annex 2 (ONR, 2018c) specific for coastal flooding hazards along with the methods by which this is incorporated into the hazard analysis process.

2 OVERVIEW OF COASTAL FLOODING, INCLUDING EROSION AND TSUNAMI IN THE UK

3. Coastal flooding is one of the most significant risks that the UK infrastructure faces with wide-ranging social, economic and environmental impacts. It is also one of the most significant risks the UK faces from climate change. Nationally, it is estimated that £150 billion of assets and 4 million people are currently at risk from coastal flooding in the UK (Environment Agency, 2009). Coastal flooding is the second highest risk for causing civil emergency in the UK, after pandemic influenza (Cabinet Office, 2015). It is a growing threat due to long-term mean sea level rise and possible future changes in storminess (Church et al., 2013) as well as continued population growth and development in flood-exposed areas (Hallegatte et al., 2013). Irrespective of any future change in storm climate (which would affect storm surges and waves) mean sea level rise will result in more instances of extreme sea level thresholds being reached.

4. Coastal flooding occurs when some combination of high tide, storm surge and wave conditions is sufficiently severe to overtop or breach coastal defences and cause inundation of low-lying areas (Figure 1). Extreme high waters around the UK are normally caused by a combination of exceptionally high tides and severe weather events. Extra-tropical cyclones (the prevailing weather systems for the UK) produce storm surges which can increase tidal levels by 3-4 m in exceptional cases. The still water level (defined as the sea level before short period waves are taken into account) can be further elevated at the coast by wave setup caused by wave breaking. Storms then also produce large wind and swell waves, which can overtop coastal defences/beaches and cause flooding and erosion.

5. The combination of high water levels and severe weather can also result in changes to beaches and nearshore bed features; which in turn can expose man-made or natural defences to greater pressures. These increased pressures, such as deeper water at the toe of the defence or localised failure of defences can then increase the potential for coastal flooding.

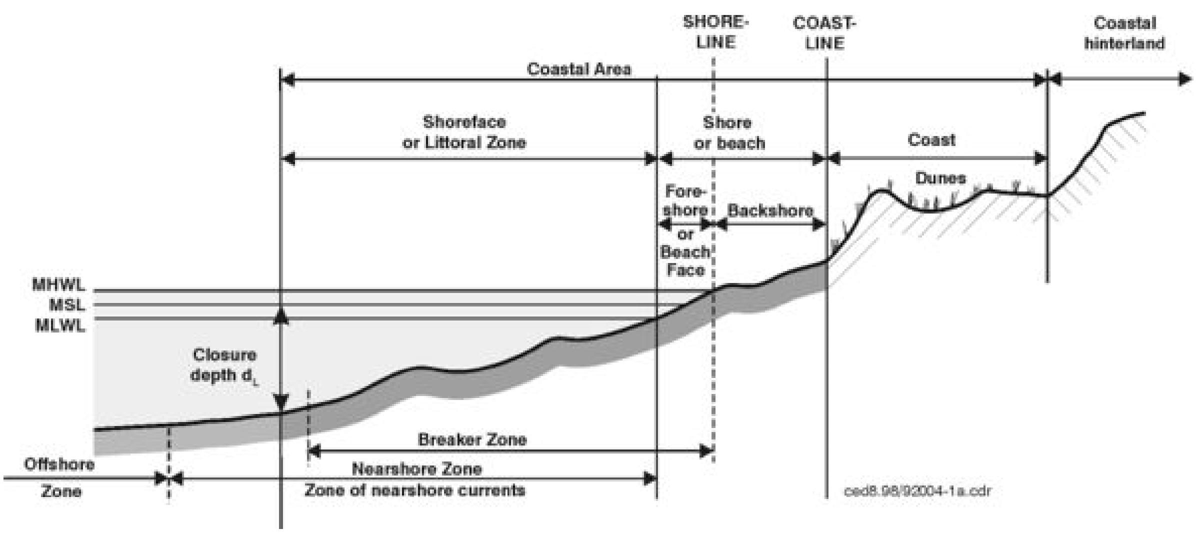

Figure 1

Definition of coastal terms, mainly from Shore Protection Manual (Coastal Engineering Research Center, 1984).

6. A further factor that drives coastal flood risk is socio-economic change (Thorne et al., 2007). Changes in land use and increasing asset values in floodplain areas have led to enhanced exposure to flooding (Horsburgh et al., 2010). This has, and is likely to lead to the provision of more forms of coastal protection which can cause changes in

coastal morphology. Changes in coastal morphology can also influence flood pathways and thus flood risk (Thorne et al., 2007; Nicholls et al., 2015). As erosion is expected to dominate coastal morphological change in the future because of mean sea level rise, this will add to the overall flood risk.

7. All components of sea level display considerable natural variability, which influences the frequency of flooding on inter-annual and multi-decadal time scales. Natural variability in the wave, storm surge and mean sea level components ranges from variability associated with stochastic (random) processes, to those displaying seasonal and longer period changes associated with regional climate (e.g. the quasi-decadal cycle known as the North Atlantic Oscillation; NAO). The UK recently experienced an unusual sequence of extreme storms over the winter of 2013-2014, resulting in some of the most significant coastal flooding since the North Sea storm surge of 1953 (Matthews et al., 2014; Haigh et al., 2016). Although no individual storm was exceptional, the persistence of storminess was very unusual (although not unprecedented). On 5th December 2013, extreme sea levels in the North Sea exceeded those of the 1953 floods at several sites (Wadey et al., 2015) resulting in damage to property and infrastructure. The subsequent storms in January and February 2014 caused widespread damage to defences, property and infrastructure on the south-western coastlines of England and Wales (most notably the collapse of the main railway line at Dawlish in Devon; Dawson et al., 2016).

8. This report also considers the risk to the UK posed by tsunami, based on expert reports that were published by the Department for Environment, Food and Rural Affairs (Defra) (Defra, 2005; 2006), and the literature therein, following the Indian Ocean tsunami of 26th December 2004.

2.1 Mean sea level

9. Sea level change at any particular location depends on many regional and local physical processes as well as global climate drivers, so regional sea level change will differ from the global average. The fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) concluded that it is very likely that the average rate of global averaged sea level rise was 1.7 mm per year between 1901 and 2010. For the more recent 1993 to 2010 period, the average rate of change was 3.2 mm per year, with a consistency between tide-gauge and satellite altimeter data. There is high confidence that the rate of observed sea level rise increased from the 19th to the 20th century (Bindoff et al., 2007; Woodworth et al., 2011) and there is evidence of a slow long-term acceleration in the rate of sea level rise throughout the 20th century (Church and White, 2011). Whether the faster rate of increase in sea level during the period from the mid-1990s reflects an increase in the longer-term trend or decadal variability is still not clear.

10. Although there is a great deal of local variability in the measured values, mean sea levels around the UK (from tide gauge records) mostly exhibit 20th century rises that are consistent with the global mean value although the central estimate around the UK is slightly lower than that of the global value (Woodworth et al., 2009).

2.2 Vertical land movement and gravitational effects

11. For planning and engineering purposes, it is sea level with respect to the local land level that is of primary interest and the solid Earth itself is also moving as it recovers from ice loading during the most recent ice age. A key process that affects vertical land motion is the viscoelastic response of the solid Earth to deglaciation, termed glacial isostatic adjustment (GIA). The most recent analysis of GIA effects for the British Isles is provided by Bradley et al. (2011). An accurate understanding of regional sea level change is a particular area which involves combining the global models of eustatic sea level change (i.e. sea level rise due to volume changes as well as geological changes

to ocean basins) with local models of GIA, modified by localised effects at the coast (e.g. Smith et al., 2012).

12. A further complication is that sea level change is affected by large scale gravitational adjustment in response to polar ice melt. Mitrovica et al*.* (2001; 2009) showed how rapid melting of major ice sources gives rise to spatial changes in the Earth's gravity field (as well as to the volume of water in the oceans); their model predicts a fall in relative sea level close to the source of melting as the gravitational interaction between ice and ocean is reduced whereas there is a correspondingly larger rise in sea level further from the melt source.

2.3 Storm surges

13. Storm surges are the large scale increase in sea level due to a storm. They can increase sea levels by 3-4 m in European coastal seas and they last from hours to days and span hundreds of square kilometres. They are caused by wind stress at the sea surface and the horizontal gradient of atmospheric pressure (Pugh and Woodworth, 2014), although the magnitude of any particular storm surge is influenced by many factors including the intensity and track of the weather system, bathymetry, and coastal topography. The same physics controls storm surges caused by mid-latitude weather systems (extra-tropical cyclones) and tropical cyclones (hurricanes). In regions of high tidal range, storm surges represent the greatest threat when they coincide with tidal high water: most operational forecasting centres now systematically refer to the combination of a storm surge and tidal high water as the storm tide.

14. In a strongly tidal nation like the UK, it is important to understand the interaction between storm surges and tides. Such interactions have been extensively studied (e.g. Rossiter, 1961; Prandle and Wolf,1978). The dominant mechanism for tide-surge interaction is that increased water levels due to meteorological forcing induce a phase shift in the tidal signal (Horsburgh and Wilson, 2007); many properties of a non-tidal residual time series (i.e. the time series of sea level observations minus tidal predictions) are simply an artefact of small changes to the timing of predicted high water. The most useful measure of storm surges is the skew surge which is the difference between the maximum observed sea level and the maximum predicted tidal level, regardless of their timing during the tidal cycle (de Vries et al.,1995). Hence each tidal cycle has one predicted high water value and one associated skew surge value. The advantage of using the skew surge is that it is a simple and unambiguous measure of the storm surge.

15. Williams et al. (2016) have now systematically proven that the magnitude of high water exerts no influence on the size of the most extreme skew surges, confirming previous studies (Environment Agency, 2011; Batstone et al., 2013). This provides a statistically robust proof for why any storm surge can occur on any tide and this is essential for understanding worst-case scenarios. The lack of any observed storm surge dependency on water depth emphasises the dominant natural variability of weather systems. Weak seasonal relationships between skew surges and tidal high waters were identified, and the inclusion of these in future statistical methods will improve the estimates of extreme sea levels (see Section 5).

2.4 Waves

16. Waves are smaller scale disturbances on the sea surface caused by the wind. Whilst waves do not affect the average height of the sea surface, they cause overtopping (intermittent pulses of water or spray over the top of a coastal defence); waves also possess considerable energy and can change nearshore bed and beach morphology. This energy, either in isolation or in combination with an altered nearshore can weaken coastal defences leading to an eventual breach. The largest waves in UK waters are found on the Atlantic boundaries of the coastline where waves can propagate over large fetches from the ocean, especially in autumn and winter when strong winds are

more intense and persistent. Instrumental wave records are available from the 20th century onwards and inter-annual variability in the wave climate is known to be strongest in the winter and can be related to atmospheric modes of variability, most notably the NAO. Swell waves are relatively long waves (periods typically 10-12 seconds) that travel long distances and are often observed a long distance from their region of generation. Swell waves and locally-formed wind waves can have different directions of propagation, and swell waves carry more energy than shorter wind waves of equivalent wave height.

17. Wave setup is a temporary increase in mean sea level due to the presence of breaking waves. As waves break, the wave energy flux decreases (due to energy dissipation) and the mean surface adjusts to balance the decreased wave radiation stress. Large waves during storm events can add up to 30 cm to mean sea level through wave setup. Wave setup and storm surges cannot be separated from a tide gauge record – they both add to the predicted tidal level.

18. All wind and wave time series show a great deal of variability including inter-annual and inter-decadal fluctuations. Rather dramatic increases in wave height occurred between 1960 and 1990, but these are now seen as just one feature within a longer history of variability (Woolf and Wolf, 2013). For example, Alexander et al. (2005) showed that wave heights increased significantly between 1950 and 1990, yet during this same period trends in wind speed around the UK were significantly weaker than for wave heights, and, therefore, the increase in wave heights is attributed to Atlantic waves propagating as swell. There is no clear pattern in results since 1990.

19. Many of the changes over the last 50 years can be understood in terms of the behaviour of the NAO (Woolf and Wolf, 2013). The trend towards stormier conditions in the NAO from the 1960s to early 1990s is unique in the record of this climate index but there is no clear connection to other aspects of climate such as global warming (Osborn, 2004).

2.5 Tides

20. Tides are periodic variations in the surface water level that result from the mutual gravitational attraction of the Earth, Moon and Sun. Most places around the UK experience two high and two low tides each day. Several recent studies have detected measurable changes in tidal range during the 20th century and early part of the 21st century at a number of locations (see Mawdsley et al., 2015 for a review). In addition, there have been a number of studies that predict changes in tidal range around the UK resulting from future changes in mean sea level (Pickering et al., 2012; Ward et al., 2012; Pelling et al., 2013). Whilst further research is needed to explain the observed global changes in tides the likely mechanisms for change are adjustments to the resonant systems of shallow seas combined with changes in energy dissipation due to increased average water depths. Typically, all these modelling studies suggest that changes in tidal range will be in the order of plus or minus 10% of the changes in mean sea level. Although small in comparison to the mean sea level changes, altered tidal ranges could enhance coastal flooding at some locations. Changes in tides, therefore, need to be considered in future assessments of extreme sea level change and coastal flooding.

2.6 Extreme sea levels

21. IPCC (2013) confirms that at most locations, mean sea level is the dominant driver of observed changes to sea level extremes although large-scale modes of variability such as the NAO may also be important. There is evidence of increases in extreme water levels over the past 100-200 years around many parts of the global coastline, including around the UK (e.g. Menendez and Woodworth, 2010). While changes in storminess could contribute to changes in sea level extremes, there is little or no evidence for either systematic long-term changes in storminess or any detectable change in storm

surges (IPCC, 2012). Allen et al. (2008) show that changes in UK storm frequency over the second half of the 20th century were dominated by the natural variability of our weather systems. The scientific consensus is that any changes in extreme sea levels at most locations worldwide have been driven by the observed rise in mean sea level (e.g. Woodworth and Blackman, 2004; Haigh et al., 2010; Menendez and Woodworth, 2010; Marcos et al., 2015; Wahl and Chambers, 2016).

2.7 Tsunamis

22. Following the Sumatra earthquake of 26th December 2004 and the devastating tsunami that followed, the UK government conducted a full review of tsunami risk. Tsunami hazard to the UK was assessed by gathering evidence on past events, considering possible source regions, and modelling the propagation of tsunami waves from plausible source locations to the coast. Studies (Defra 2005; Defra, 2006) concluded that a tsunami reaching the UK from the Azores-Gibraltar fault zone (which was responsible for the earthquake and tsunami causing the destruction of Lisbon in 1755) is the most likely event to affect the UK coastline.

23. In the modelling carried out for these studies, the projected heights of tsunami waves arriving close to the shore were comparable to those seen in typical storm surges. All areas potentially affected by the plausible range of tsunami wave heights have flood defence infrastructure designed to protect against waves of those sizes. However, certain characteristics of tsunami events (the number of waves, the range of typically longer wavelengths) are likely to create sea conditions different to those during a storm surge. The momentum associated with longer wavelength tsunami waves, and volume of water within a wave crest, result in incident wave energy that is significantly greater than for wind waves of the same height. Therefore, it should not be assumed that the impact of a tsunami would be comparable to that of a storm surge simply on the basis of similar wave heights and water levels. Also, tsunami events could occur at any time. They are not associated with adverse meteorological conditions so cannot be predicted in advance, although relatively expensive monitoring systems could give some degree of early warning.

24. There is geological evidence for a major tsunami impacting the coasts of Scotland and northeast England following a submarine landslide on the Norwegian continental shelf approximately 8200 years ago. Mapping of tsunami deposits suggests that this landslide generated a tsunami that may have caused waves to reach more than 6 metres locally above the sea level at that time: however, large uncertainty surrounds these values since, whilst there is clear local sedimentary evidence, the coastal configuration, nearshore bathymetry, past sea levels and lack of knowledge of the tidal state at the time makes an accurate estimate of wave height difficult. Geological data suggest that large submarine landslides (submarine mass failures) in the critical region have occurred before although none have been shown to affect the UK. Whilst new research is aimed at better quantifying the hazard to the UK from landslide tsunamis (see Section 8), the Defra (2005; 2006) reports remain the most authoritative guides to tsunami hazard to the UK.

2.8 Meteorological tsunamis

25. Around the UK the sea level variability largely occurs over periods from hours to days and is associated with extra-tropical storms (our weather systems). However, there is an increasing recognition that higher-frequency sea level variations in the order of minutes to hours can also raise sea levels. Often referred to as ‘meteorological tsunamis’ or ‘meteotsunamis’ these are generated by traveling atmospheric disturbances such as thunderstorms or squall lines (Vilibić et al., 2016). They have the similar spatial and temporal scales as ordinary tsunami waves and can affect some coastal areas causing extreme resonant conditions in bays and harbours, although they are normally far less hazardous than tsunamis caused by earthquakes. Whilst they are a genuine hazard elsewhere (e.g. Japan, the Mediterranean and Adriatic

Seas) they have very small amplitudes in other European coastal waters. Meteotsunamis around the UK typically involve a wave of 20-30cm (Tappin et al., 2013; Sibley et al., 2016; Ozsoy et al., 2016) - far smaller than typical storm surges - although occasionally they can cause nuisance flooding of low lying areas.

3 UK PROJECTION OF SEA LEVEL AND SEA LEVEL EXTREMES IN RESPONSE TO CLIMATE CHANGE

26. Sea level projections for the UK are set out in the UK Climate Projections 2009, UKCP09 (Lowe et al., 2009). The methods used to generate sea level projections for the UK (see Section 6 herein) use ensemble projections from IPCC climate models (IPCC, 2007). A model ensemble (see Annex 2, ONR, 2018c) is a suite of models with inherent differences (in code, or treatment of physical processes, or conditions at the beginning of model runs) that allows a useful and meaningful average to be taken of those model predictions. The IPCC Fifth Assessment Report (AR5) (IPCC, 2013) uses a different set of future pathways of greenhouse gas forcing, which were not available at the time of producing UKCP09. Furthermore, the precise method of calculating sea level changes, and the baseline period were different compared to the previous IPCC report (IPCC, 2007). UKCP09 projections and advice will be replaced in due course with updated projections in a new framework called UK Climate Projections 2018, UKCP18 (planned for release in late 2018).

27. IPCC (2013) has projected global sea level rise for the period 2081 to 2100, compared to 1986 to 2005, of 0.29 m to 0.82 m. The precise range varies with the assumed Representative Concentration Pathway (RCP) scenario which describes the radiative imbalance in the Earth’s atmosphere due to greenhouse gas emissions. Unlike in the previous IPCC report (AR4) (IPCC, 2007), these projections now include a contribution from changes in ice-sheet outflow, for which the central projection is 0.11 m (it should be noted that there is only medium confidence in the range of projected contributions from models of ice sheet dynamics). Nevertheless, these new projections are broadly similar to those in the earlier AR4 assessment (IPCC, 2007) upon which UKCP09 is based. It is very likely that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1970-2010 for all RCP scenarios. Regional patterns of sea level change in the 21st century still differ between models. However, about 70% of the global coastlines are projected to experience a sea level change within 20% of the global mean sea level change.

28. Some studies use simple statistical, so-called ‘semi-empirical’, models that relate 20th century (e.g. Rahmstorf, 2007) or longer (e.g. Vermeer and Rahmstorf, 2009; Grinsted et al., 2010) temperature or radiative forcing (Jevrejeva et al., 2010) with sea level rise, in order to extrapolate future global mean sea level. These models are motivated by evidence in the palaeo record of a connection between global mean sea level and temperature over glacial/interglacial timescales. These models result in a wider range, and typically larger, projections of sea level rise than those obtained from physical process-based models. For example, Rahmstorf (2007) projected sea level rise by 2100 under a range of climate scenarios as being between 0.50 m to 1.40 m, and Vermeer and Rahmstorf (2009) suggested the higher range 0.75 m to 1.90 m. Church et al. (2011) note that these models may overestimate future sea levels because of the exclusion of key non-linear processes and climate feedback mechanisms. Also, future rates of sea level rise may correlate less well with global mean temperature if ice sheet dynamics play an increased role in the future.

29. There is low confidence in future storm surge and wave height projections because of the lack of consistency between models, and limitations in the model capability to simulate extreme winds (IPCC, 2012). Whilst extreme sea levels could change in the future, both as a result of changes in atmospheric storminess and of mean sea level rise, it is very likely that mean sea level rise will continue to be the dominant control on positive trends in extreme future coastal water levels.

3.1 Summary of UK national climate advice and guidelines

30. The leading source of climate change information for the UK, including changes to sea level, is called UK Climate Projections or UKCP09. Funded by a number of agencies

and led by Defra its remit is to help users assess their climate risks and plan how to adapt to a changing climate (UK Climate Projections, 2009).

31. The Marine and Coastal Projections report provides a set of scenarios that may be used to assess how vulnerable particular sites or sectors are to future climate change. The report considers the marine environment from the coastal zone and into the waters of the shelf seas around the UK (Lowe et al., 2009).

32. Further guidance is given in an assessment completed by the Environment Agency between 2013 and 2015 using UKCP09 data, to produce more representative climate change allowances for England (EA, 2016).

33. Following the Paris Agreement on Climate Change in December 2015, the UK Climate Projections will have a major upgrade, called UKCP18, to make sure decision-makers have the most up-to-date information on the future of our climate. This was announced by Defra on 15 January 2016 and will be completed during 2018 (UK Climate Projections, 2018). It is anticipated that an extreme climate change scenario analogous to the H++ scenario will also be provided with UKCP18, (this will not necessarily be released at the same time as UKCP18 but may follow shortly thereafter).

34. The Marine Climate Change Impacts Partnership (MCCIP) provides a co-ordinating framework for high quality evidence on UK marine climate change impacts, and guidance on adaptation and related advice, to policy advisors and decision-makers (MCCIP, 2018).

4 DATA SOURCES FOR COASTAL FLOODING HAZARD ANALYSIS

4.1 Bathymetric and topographic data

35. Waves and water levels at the shore are normally influenced by the shape of the seabed, which may, in turn, be subject to processes of erosion and deposition. Even areas of hard rock may be occasionally covered by depositional features such as sandbanks. The availability of contemporary bathymetric data is, therefore, normally critical to the accurate assessment of coastal flood risk. Historic bathymetric data may also be needed to build understanding of how seabed features may be changing.

36. Charts are usually used to gain information on seabed form and development. Digital copies are usually acquired (emapsite.com is currently a leading supplier) and these may be in the form of vector datasets of bathymetric contours (isobaths) or raster charts where depth is indicated by pixel colour.

37. A Digital Elevation Model (DEM) of the seabed is needed in order to numerically model the effect of bathymetry on waves or surge. Such data (ideally from ‘multibeam’ sonar, see below) can often be freely sourced from online portals such as the Channel Coastal Observatory (CCO) and the UK Hydrographic Office Inspire portal.

38. Where a quality DEM is unavailable, or is out of date (perhaps due to the possible migration of seabed features) a bespoke bathymetric survey may be commissioned from a hydrographic surveying company. This may be one element of a larger study to capture broader meteorological and oceanographic (‘metocean’) data. High quality bathymetric data is normally recorded using sonar equipment in which sound waves are emitted from a moving vessel and their echo is recorded to calculate depth. Such sonar systems may be ‘single beam’ or the more detailed ‘multibeam’ (or ‘swathe’). Difficulties are typically encountered in inaccessible shallow waters and this may be important because of the strong transformations undergone by waves in the nearshore zone. Depths might be recorded in this area using airborne Light Detection and Ranging (LiDAR) equipment, which utilises a scanning laser to measure distance. However, this approach is hampered by the normally strong attenuation of the laser beam as it passes through (often turbid) seawater.

39. If flown at low tide, terrestrial LiDAR surveys can provide shore topographic data that can be joined to bathymetric data. LiDAR data is available for most (possibly all) of the UK coast, from portals such as the Environment Agency’s *data.gov.uk* or the CCO. Care is needed to avoid errors arising from differences in datum levels between datasets. Shore profile data recorded through ongoing strategic monitoring programmes can also be useful to extend bathymetric data. In many places this monitoring will include regular surveys of intertidal shore profiles, with less frequent ‘long’ profiles extending into deeper water. Such profile data may be obtained from the Environment Agency or online data portals such as the Coastal Explorer portal or the CCO.

40. Topographic LiDAR data is also typically utilised in assessments of coastal flooding for mapping of flood extents, and to support assessment of wave overtopping. This data is normally supplemented with ground-based topographic survey data to provide detail of coastal form and sea defence structures that cannot be reliably obtained from LiDAR datasets. Other free (e.g. Ordnance Survey) and commercial sources of topographic data of varying resolution are also available.

4.2 Tide gauge and observed wave data

41. All sea level data from the UK Class A tide gauge network are available from the British Oceanographic Data Centre which has a special responsibility for the remote monitoring and retrieval of sea level data from the network. Daily checks are kept on the performance of the gauges and the data is downloaded weekly. These are then

processed and quality controlled prior to being made available for scientific use. The network includes 43 gauges, most of which are related through the national levelling network to Ordnance Datum Newlyn. Data is collected, processed and archived centrally to provide long time series of reliable and accurate sea levels which are then suitable for statistical analysis of extreme sea levels. Processed data from the tide gauge network from 1915 onwards are available free of charge. Other sea level datasets for certain locations are held by the Environment Agency and by various port authorities.

42. Since 2002, the WaveNet system has been operated by the Centre for Environment, Fisheries and Aquaculture Science (Cefas). WaveNet collects and processes data from the Cefas-operated Waverider buoys, tethered at strategic locations around the UK coastline. The WaveNet system also gathers wave data from a variety of third party platforms and programmes (industry and public sector-funded), all of which are freely available for visualisation on the WaveNet website (WaveNet, 2018). The data is used to improve operational wave and storm surge models and, on a longer timescale, the data can provide coastal engineers and scientists with a better understanding of the wave climate when designing coastal flood defences and as evidence for climate change studies. Data is available for download from the WaveNet website (WaveNet, 2018).

43. Another source of wave data, albeit for a number of limited areas, is the National Network of Regional Coastal Monitoring Programmes of England. Real time wave data is available from their website.

4.3 Use of historical and geological (Palaeoceanographic) data

44. To provide additional context, or in the absence of lengthy observational records, historical records of high water levels (e.g. Dawson et al., 2010) exist in scientific literature and are useful. However, care in interpretation is required as many are based on anecdotal observations rather than scientific instrumentation. Although such data is highly variable in quality, when taken with instrumental and coastal stratigraphic records, they can provide a useful longer-term context for identification of trends and changes in storminess. Geological evidence for the 2000 years prior to the advent of historical records and later instrumental records is also sometimes useful. Studies of geological evidence for storminess change have examined the record of sand dune movement (e.g. Gilbertson et al., 1999; Dawson et al., 2004). These studies consider the stratigraphic record of blown sand horizons within peat and / or episodes of sand movement associated with archaeological evidence. A second approach is to study cliff top storm deposits, notably in Shetland (e.g. Hansom and Hall, 2009), but thus far only the most recent events have been recognised and longer term frequency of storms not determined.

4.4 Coastal flooding databases

45. In order to better understand historical magnitudes and footprints of coastal flooding events, a UK wide systematic database of extreme sea level and coastal flooding has been compiled, covering the last 100 years (Haigh et al., 2015; SurgeWatch, 2018). Using records from the UK National tide gauge network, all sea levels that reached or exceed the 1 in 5 year return level were identified. These were attributed to 96 distinct storms, the dates of which were used as a chronological base from which to investigate whether historical documentation exists for a concurrent coastal flood. For each event the database contains information about: the storm that generated that event; the sea levels recorded during the event; and the occurrence and severity of coastal flooding that resulted. This database is continuously updated.

5 USE OF STATISTICAL METHODS IN ANALYSIS OF COASTAL FLOODING HAZARD

46. The need for consistent and improved national estimates of extreme sea levels, combined with the increase in available sea level data since previous national studies by Dixon and Tawn (1994; 1995; 1997), led to the production of an updated UK database of extreme sea levels (Batstone et al., 2013; Environment Agency, 2016). A new method termed the Skew Surge Joint Probability Method (SSJPM) was used with the aim of correcting inadequacies associated with previous methods. Methods to derive extreme sea levels have evolved with advances in the understanding and modelling of tide and surge processes and improvements in recorded data quality and length (see Batstone et al., 2013, for a complete description).

47. Joint Probability Methods (JPM) produce a probability distribution of extreme sea levels for a given location by combining statistically the separate distributions of tides[2] and storm surges (and in some cases waves too). When storm surges are involved, JPMs are superior to other methods of sea level extreme estimation (Tawn, 1992) because they use all the storm surge data in a tide gauge record. JPMs are essential in environments where the tidal signal is of comparable magnitude to the storm surge (Haigh et al., 2010) and are also superior to threshold-driven methods (e.g. Tebaldi et al., 2012) which may not detect large storm surges on small tides. The first-order independence of skew surge and tidal high water (Williams et al., 2016) removes the need for artificial statistical functions or multivariate approaches to the estimation of extreme sea levels. However, the seasonal relationships that exist between tidal high water and skew surges could be represented by multivariate, or other more complex (Kergadallan et al., 2014) methods. The best known illustration of seasonal coincidence is that around the UK the biggest tides of any year occur at the equinoxes (in March and September) and there is more chance of stormy weather then than in the summer months.

48. In the SSJPM of Batstone et al. (2013), a parametric statistical model was used to estimate the upper tail of the skew surge distribution by fitting a generalised pareto distribution (GPD) above a chosen threshold and using the empirical distribution of skew surges (from the observed tide gauge record) below this threshold. A high quantile (97.5%) was chosen as the threshold based on exploratory analysis of each dataset. For each tide gauge analysed, the two parameters of the GPD were estimated using the method of maximum likelihood. The probability distribution of extreme sea levels was evaluated by combining the deterministic tidal high waters with the statistically derived skew surge distribution, assuming the two to be independent to first order. This was shown to be true by Batstone et al. (2013) and has been confirmed in a more complete analysis for the North Atlantic by Williams et al. (2016).

49. Extreme sea levels derived in this way are assigned a Return Period (RP) which describes the probability of a particular level being exceeded in any one year. For example, the 1 in 1000 year return level is the level whose probability of being exceeded in any year is 1/1000, or 0.1%. As with all probabilities, great care must be taken in interpreting RPs: the fact that a particularly large sea level has recently occurred does not preclude another happening the following week due to the nature of the weather and the tendency for larger than average tides to occur with known periodicity. So, a period of stormy weather around extreme high tides (e.g. during the equinoxes of March and September) could easily result in successive 10 or 50 year return levels.

50. For the SSJPM, uncertainties are expressed in terms of upper and lower 95% confidence limits. These can be calculated using a so-called boot-strapping technique whereby thousands of synthetic time series of skew surges are created from the

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[2] Whilst tides are deterministic one can still generate a probability distribution of a particular height occurring over a given period.

derived skew surge probability density function. Each of the synthetic time series is then used to derive a new skew surge probability distribution. For each return level, the 2.5 and 97.5 percentiles of the ensemble of generated values are used to define the 95% confidence interval. It should be noted that the range of uncertainty associated with the 10,000 year return period can be very high, typically 1-2 m. This is unavoidable with a data-driven method where tide gauge records are typically a few tens of years and seldom provide more than 100 years of data. The largest source of uncertainty is the calculation of the GPD parameters associated with the upper tail of the skew surge distribution; other sources of uncertainty for UK extreme sea level estimates are described in detail by Batstone et al. (2013).

51. Clustering of extreme sea levels (i.e. several storms in a short period of time) can lead to amplified flood damages due to attritional effects on defences and inadequate recovery time of natural (e.g. beaches) and human elements within the system (Wadey et al., 2014). At a single location, the statistical significance of storm clustering is accounted for by a parameter called the extremal index. This ensures that a single storm only contributes once to the statistical method even if it spans more than one tidal cycle. Estimates of extreme sea levels may be improved further by the development and use of statistical methods that represent the combined spatial footprint (areal extent) and clustering of storm events.

52. Tide gauges are the best source of sea level data that can be used in the statistical methods described. However, tide gauges are geographically sparse and hydrodynamic models can be used to simulate sea levels between gauged sites, in order to determine how extremes are likely to vary from one gauge to the next. In the most recent national evaluation of extreme sea levels (Batstone et al., 2013; Environment Agency, 2011), the primary estimates were derived using tide gauge data and SSJPM and then coastal ocean models were used to interpolate estimates of extreme sea levels at intermediate locations.

53. A further consideration for extreme water levels is the combination of extreme still water level (i.e. the tide plus storm surge) with large waves and their subsequent overtopping of defences. The most commonly used joint probability approach for waves and sea level is encapsulated in the JOIN-SEA software which is provided by HR Wallingford (HR Wallingford, 2000) and is also described by the Defra/ Environment Agency best practice guide (Defra/EA, 2005). There are generally two types of methods employed. Deterministic design-storm approaches that use joint exceedance contours with a specified annual exceedance probability, and risk-based approaches. It is well-established that design-storm approaches do not facilitate a direct estimate of the annual exceedance (return period) of wave overtopping rates and the associated flood hazard. This method tends to underestimate flood hazards unless correction factors are applied (HR Wallingford, 2000, Hawkes et al., 2002, Defra/EA, 2005, Gouldby et al., 2014; 2017). Risk-based methods provide a direct estimate of annual exceedance overtopping rates and related flood hazards.

54. Within extreme wave and sea level joint probability analyses, the statistical modelling is typically undertaken offshore in deep water. This minimises the potential for physically implausible extrapolations (which are likely in the nearshore region). When the analysis is conducted offshore, wave heights are often derived from numerical models (e.g. the Met. Office European Wave Model) or even offshore wave measurements. These offshore conditions have to be transformed to the nearshore taking account of various physical processes, using an appropriate wave model such as SWAN (Simulating WAves Nearshore, Booij et al., 1999), see Section 7 for more detail. The marginal extreme wave heights can be derived at specific offshore model locations by fitting a GPD to the model data.

6 ANALYSIS OF COASTAL FLOODING HAZARD - STILL WATER LEVEL

55. The most recent published interpretations of sea level change for the UK are set out in the UK Climate Projections 2009 (Lowe et al., 2009). As previously stated, ensemble projections from the IPCC AR4 models (IPCC, 2007) were used to generate these sea level changes. As an illustration, Table 1 below, shows the sea level change, excluding vertical land movements, for the UK for three emissions scenarios over the 21st century.

Emissions scenario[3]	5th percentile	Central estimate	95th percentile
High	15	46	76
Medium	13	37	61
Low	12	30	48

Table 1

Modified from UKCP09 (Lowe et al., 2009). UK mean sea level change (cm) over the 21st century including ice melt, under three different scenarios, with 5th to 95th percentile confidence intervals. The changes relate to the periods 1980–1999 to 2090–2099.

56. Combining vertical land movements with the projected sea level changes gives an estimate of the local sea level rise for the low, medium and high emissions scenarios. The vertical velocities of the Earth's crust that were used in UKCP09 were taken from Bradley et al. (2008) and were treated as constant for the 21st century projections. Vertical land movement was calculated for four sample locations (London, Cardiff, Edinburgh and Belfast). Once land movement is included, slightly larger sea level rise projections are obtained in southern parts of the UK where land is subsiding, and somewhat lower increases in sea level for the north. UKCP09 gives sea level increases (including vertical land movement) for 1990–2095 of approximately 21–68 cm for London and 7–54 cm for Edinburgh. The ranges refer to the most likely spread of values (5th to 95th percentiles) from the medium emissions scenario. The full spread of results can be found in Lowe et al. (2009). Updated values for vertical crustal motions are now available (Shennan et al., 2012) but differ negligibly from those used in the UKCP09 arithmetic.

57. On the basis of UKCP09 projections, Defra and the EA have produced sector-specific flood and coastal risk guidance documents (e.g. Environment Agency, 2016).

58. UKCP09 provided a high-end so-called 'H++' scenario to aid contingency planning, and whose value justifies the numerous assumptions made. This low probability, high impact, value was estimated at 1.9m, consistent with physical constraints on glacier movement (Pfeffer et al., 2008); this value also encompasses the majority of semi-empirical model projections. For comparison, Katsman et al. (2011) used an alternative method to develop a high-end scenario of 0.40 m to 1.05 m sea level rise (excluding land subsidence) on the coast of the Netherlands by 2100. More recently, Jevrejeva et al. (2014) obtained a probability density function of global sea level at 2100, suggesting that there is a 5% or smaller probability of global sea level rise greater than 1.8 m; this low probability upper limit combined expert opinion and process studies and also indicates that other lines of evidence are needed to justify any larger sea level rise this century.

59. As noted previously, the IPCC Fifth Assessment Report (AR5; IPCC, 2013) uses a different set of future pathways of greenhouse gas forcing, which results in broadly similar projections of future sea level changes with some key differences. The climate analyses of UKCP09 will be updated in a new framework, UKCP18 (see link in Section 3, paragraph 33). The IPCC Fifth Assessment Report considers that it is very likely that

[3] In comparison, the UKCP09 H++ scenario range for time-mean sea level rise around the UK is 93 cm to approximately 1.9 m – see paragraph 58.

there will be a significant increase in the occurrence of future sea level extremes by 2050 and 2100, with the increase being primarily the result of increases in mean sea level. Storm surge and wave projections for the UK depend on global climate models (ONR, 2018c) producing consistent and accurate simulation of the North Atlantic storm track. At the present time, there is low confidence and as yet no consensus on the future storm surge and wave climate, stemming from diverse projections of future storm track behaviour.

60. Substantial rises in mean sea level are likely to result in changes to the shelf sea tides. The change in mean sea level affects the phase speed of the tidal wave, which in turn modifies the tidal resonance in the European shelf seas. Any modification to the tide is highly spatially variable, but in places the change in tidal amplitude can be as much as 20% of assumed mean sea level rise. This could lead to some local changes (increases or decrease) in the spring tidal range of over 0.2 m, if a mean sea level rise of 1 m is obtained.

61. It is very likely that global mean sea level rise will continue beyond the 21st century. The thermal expansion of the ocean to increased temperatures takes place over centuries to millennia; so thermal expansion will continue beyond 2100 even if greenhouse gas concentrations are stabilised immediately (which is unlikely). Contributions to sea level rise from ice sheets are expected to continue beyond 2100, but glacier contributions will decrease as the amount of glacial ice diminishes. Some models suggest sea level rises of between 1-3 m in response to CO_2 concentrations above 700 ppm. Studies of the last interglacial period (e.g. Kopp et al., 2009) indicate a very high probability of a sea level rise of 2 m over 1000 years, and cannot rule out values in excess of 4m.

7 ANALYSIS METHODS FOR SHORELINE EVOLUTION, NEARSHORE WAVE TRANSFORMATION AND INTERACTION (FOR THE DESIGN OF FLOOD DEFENCES AND UNDERSTANDING COASTAL EROSION)

62. Analysis of the interaction between coastal sea levels (tides, storm surges, wave conditions) and the local shoreline for the purpose of designing flood defences is necessarily site-specific, and considers smaller scales and local processes. An overview of typical coastal defence structures found in the UK relevant to the analysis of coastal flooding and erosion at UK nuclear sites is given in Annex 3 of TAG 13 (ONR, 2018b). Understanding local transformational processes on waves and currents requires the best available local data for bathymetry, topography and sediment type. Significant changes to coastal geomorphology can occur over timescales of 10-100 years, and shoreline analysis uses coupled hydrodynamic and sediment transport models to assess plausible future bathymetric and topographic scenarios. For model simulations to be effective, they must be based on the best possible data for bathymetry and sea bed material, forced by realistic worse case scenarios of sea level and meteorological conditions. Different future geomorphologies can result in significantly different nearshore wave fields impinging on engineering structures.

63. Long term (order 100 years) coastal erosion rates for the coast of England and Wales have been provided by the Foresight Flood and Coastal Defence Project (Foresight, 2004) and results suggest that 28% of the coast is experiencing erosion rates in excess of 10cm per year (Burgess et al., 2007). However, Burgess et al. (2002) argue that 67% of the coastline is under threat since a significant fraction of the coastline is held in position by engineering measures. Where a coastline is protected by engineering structures, increases in sea level result in a steepening of the intertidal beach profile, known as coastal squeeze. According to Taylor et al. (2004), almost two-thirds of intertidal profiles in England and Wales have steepened over the past hundred years.

64. A number of predictive models have been developed to improve our understanding of coastal erosional processes, and these models tend to focus on particular typologies of coastlines. A full review of coastal evolution models for different coastal types is given by Masselink and Russell (2013). The Soft Cliff and Platform Erosion (SCAPE) model (Walkden and Hall, 2005) was used to assess erosion in Essex and predicted that a tripling in sea level rise (from 2mm to 6mm per year) resulted in a 15% increase in cliff recession. The same model has been use to develop climate change and management scenarios for the Norfolk coastline (Walkden et al., 2008). Brooks and Spencer (2012) applied SCAPE to the Suffolk coast and predicted that volumes of sediment released by erosion in the 21st century due to mean sea level rise will increase by about an order of magnitude above the sediment release estimates for the early 20th century. All these results convey the physical fact that increased sea levels will expose increased areas of soft cliff to wave action.

65. Different modelling approaches are applied to morphological change in estuaries. One widely used example is the ASMITA model (Aggregated Scale Morphological Interaction between Inlets and Adjacent coast; Stive et al., 1998) which represents the estuary as a series of morphological elements (tidal flat, channel, etc). This model has been applied to the Thames estuary where it predicted that over the next century the estuary will experience accretion less than the predicted rate of sea level rise, resulting in a deepening of the estuary by up to 0.5m (Rossington and Spearman, 2009).

66. Having defined any future, plausible coastline, evaluating the interaction of extreme nearshore wave conditions with coastal topography and defences requires offshore wave fields to be transformed using a suitable wave transformation model. As offshore waves enter shallower water they are modified by a number of physical processes (e.g. diffraction, refraction, shoaling, wave breaking) as well as influences of local winds and tidal currents. Consequently, the waves impinging on coastal structures can have very different properties to offshore waves. A recent and thorough review of wave

transformation models has been provided by Lawless et al., (2016), as part of a wider review of best practice for coastal flood forecasting, commissioned by the Environment Agency. This guidance document also lays down required standards of accuracy for all elements of sea level forecasting (tide, surge, wave, overtopping) and is intended to maximise consistency in coastal flood forecasting across the spectrum of models used by coastal engineers. The role of these models is described briefly below, but refer to Lawless et al. (2016) for more details.

67. Phase-averaging spectral wave models such as SWAN, (Booij et al., 1999) compute the two-dimensional (2D) wave spectral energy in a similar way to offshore wave models by solving the action balance equation. They can be run on either a regular or irregular grid and they derive wave parameters such as significant wave height, wave period and wave direction. These models are forced at their seaward boundary by offshore wave and wind conditions, and they represent the majority of wave transformation processes. Other models in this class include MIKE21-SW (MIKE, 2018), STWAVE (AQUAVEO, 2018) and TOMAWAC (open TELEMAC-MASCARET, 2018). These models typically resolve bathymetric features of ~100 m size but are not routinely used at finer resolution due to computational intensity. A common approach – so-called hybrid approach - is to combine a wide area 2D wave model with a series of one-dimensional (1D) wave models to transform waves from the tidal low water contour to specific beaches or structures.

68. More complex wave transformation models, so-called phase-resolving models, exist to account explicitly for diffraction and refraction by solving the mild slope equation. Explicit representation of individual waves is also possible but is computationally demanding. A full list of this type of model is provided by Lawless et al. (2016). Because these models simulate individual waves, their spatial resolution is typically a few metres. This renders them suitable for the analysis of specific sites (and the effect of specific waves), but not wide area forecasting.

69. Wave transformation models depend on accurate bathymetry. To model the transformation from offshore to a specific structure will normally require some combination of charted bathymetric data (e.g. from Admiralty or other surveys) and accurate beach profile data from LiDAR. For many parts of England and Wales, LiDAR data is held by the Environment Agency (see Section 4.1 of this document).

70. Wave transformation models require careful validation, based on a selection of storm events. Ideally, waves inshore will be measured with suitable devices (e.g. Waverider buoys). Measured wave data for the UK is available from Wavenet, the Met. Office, and the Channel Coastal Observatory. Hindcast waves and atmospheric forcing can be derived from the operational Wavewatch III model run at the UK Met. Office.

71. A number of studies have shown that joint probability contouring approaches, that use a joint exceedance approach to define annual exceedance contours of waves and sea levels, do not facilitate a direct estimate of the annual exceedance of structural responses (e.g. Wave overtopping rate) and the related flood hazard (HR Wallingford, 2000; Hawkes et al., 2002; Defra/EA, 2005; Gouldby et al., 2017). The joint probability contouring approach tends to underestimate flood risk unless correction factors are applied to account for this known discrepancy. To obtain an unbiased estimate of coastal flood hazards, it is necessary to adopt a risk-based approach. In this approach, the multivariate extreme value distribution is integrated over the outcome variable of interest (e.g. wave overtopping or floodplain flood depth). The JOIN-SEA software was developed to implement this approach (HR Wallingford, 2000). More recently, advances in the underlying statistical models (Heffernan and Tawn, 2004) have been applied to asses coastal flooding using a risk-based approach at a national scale. Offshore waves, winds and sea levels have been extrapolated to extremes, these have then been transformed to the nearshore and through to overtopping rates using the SWAN wave model combined with statistical emulators and an empirical wave overtopping model to directly estimate wave overtopping annual exceedance

probabilities and the related flood risk. Gouldby et al. (2017) used a statistical emulator and the SWAN model to derive a national set of extreme events at a 1 km resolution in the nearshore region.

72. Extreme combinations of waves and sea level lead to wave overtopping which occurs when waves run up the face of a seawall or dike and pass over the crest of the structure (so-called ‘green-water’). In cases where the structure is vertical, the wave may impact against the wall and send a plume of water over the crest. A different form of overtopping occurs when waves break on the seaward face of the structure and produce significant volumes of splash and spray, which may then be carried over the wall either under their own momentum or by an onshore wind. Whether overtopping discharges are by green-water, plume or splash, the consequences will tend to vary according to circumstances. Typically, green-water and plume overtopping will be associated with flood inundation and structural damage, whereas spray will be associated with personal safety and also incremental damage to buildings.

73. Analysis of wave overtopping of structures is complex and there are a range of prediction methods that are adopted in practice, all of which are complex and have associated uncertainties. These methods include structure-specific empirical formulae detailed within EurOtop (Pullen et al., 2008; EurOTop, 2016), generic empirical metamodeling approaches involving neural networks (e.g. Van Ghent, 2007; Kingston, 2008; Zanuttigh et al., 2016), numerical models (also referred to as Computational Fluid Dynamics or CFD models) that solve the full 3D Navier Stokes Equations (Hirt and Nichols, 1981; Chen et al., 2016; and Dimakopoulos et al., 2014), and finally laboratory based, scaled physical model experiments. All of the empirical approaches are based on functions fitted to data from physical model experiments. This is because measured overtopping rates are rare and laboratory data is generally considered the next most reliable source of data. The empirical EurOtop methods are generally applicable when the structures are of standard geometry. Where structures deviate from standard geometry, the meta-modelling approaches are often employed as they facilitate interpolation to non-standard geometry. Numerical models that simulate the physical processes can be challenging to calibrate and these are often employed in parallel with physical models.

74. The rate of wave overtopping is generally presented as a mean discharge per metre run of seawall, averaged over approximately 1000 waves. Whilst mean discharge is convenient for analysis of flood volume, the instantaneous hazards to people or building damage are more closely correlated to individual wave volumes and / or velocities. For the analysis of individual wave overtopping volumes and velocities, CFD and physical models offer the most robust estimates.

8 ANALYSIS OF TSUNAMI HAZARD

75. For the UK and Europe there are records of several past events of significance, notably, in historical times, the earthquake of 1st November 1755 and the ensuing tsunami that, together, destroyed Lisbon. There is also firm geological evidence for the source region and the effects of a major tsunami impacting the coasts of Scotland and northeast England following a submarine landslide offshore Norway about 8200 years ago. The evidence that tsunamis have reached the UK in the past indicates that the possibility of significant future events cannot be dismissed. Also, there may be other potential sources of future tsunami.

76. The Defra (2005) study found that a tsunami reaching the UK from the Azores-Gibraltar region (the region responsible for the earthquake and tsunami causing the destruction of Lisbon in 1755) is a possible event. However, the likelihood of a future tsunami from this source being worse than that of 1755 is negligible. A tsunami resulting from a landslide on the Canary Islands would be heavily dependent on the nature of the collapse. Some reports (e.g. Ward and Day, 2001) have suggested that the western flank of La Palma, in the Canary Islands, is vulnerable to collapse, with devastating effects around much of the North Atlantic coastline. Whether a tsunami generated by a flank collapse was capable of crossing large distances or not would depend entirely on the nature of the event; a coherent large block entering the sea with high acceleration would produce such an effect, but if the slope failure were composite or less energetic, the effects produced would be local. Studies of the offshore turbidites created by landslides from the flanks of the Canary Islands suggest that these result from multiple landslides spread over periods of several days. Separate failures occurring over this time scale would each generate a discrete tsunami, but these successive failures are too widely spaced in time to have a cumulative effect on tsunami magnitude (Wynn and Masson, 2003). All the submarine landslides so far studied in detail around the Canary Islands indicate that they are multiple events, implying smaller scale tsunamis. The results of the tsunami propagation modelling carried out in Defra (2005) are summarised in the table below.

Tsunami source	Height and propagation time of wave reaching the coast, regions affected and (assumed amplitude of wave at its origin)
Near field earthquake in North Sea (cf. Dogger Bank, 1931)	0.8-2m 1-2 hours Yorkshire and Humberside coasts (1m)
Passive margin earthquake in the western Celtic Sea	0.5-1m 3-6 hours North Devon, Bristol Channel, South and West Wales (1m)
Plate boundary west of Gibraltar (Lisbon earthquake of 1755)	0.8-1m 5-8 hours Cornwall, North Devon and Bristol Channel, South Wales (1m)
La Palma slide (Canary Islands)	1-2m 7-8 hours Cornwall, North and South Devon (2m)

Table 2

Results from the tsunami modelling exercise in Defra (2005) with the most plausible tsunami sources for the UK

77. Geologically, an earthquake in the North Sea sufficiently large to cause a tsunami is possible although there is no record of any such event. A model of a credible North Sea event centred on the location of the 1931 earthquake gave wave heights along eastern UK coasts of 1-2 m.

78. To provide a more detailed assessment of the potential hazard, the Defra (2006) study focused on a near coastal North Sea event and a more detailed analysis of a Lisbon 1755 type event. The model studies of the Lisbon 1755 event explored the effects of a variety of plausible earthquake magnitudes and fault orientations. Larger magnitude earthquakes produced tsunami waves with typical wave amplitudes of 1-2 m around the south west of the UK, with 3-4m waves in localised bays. Whilst the size of these tsunami waves are comparable to those in typical storm surges, certain characteristics of tsunamis are likely to create sea conditions different to those during a storm surge. The model study of the near-coast event in the North Sea was centred on the location of the 1931 earthquake, with an assumed magnitude of **M**6.0. The resulting tsunami was propagated through high resolution storm surge and wave models in order to estimate the wave run up and inundation on a variety of beach slopes.

79. The model results were used to assess hazard at the coastline. As the tide did not interact with the tsunami wave, the analysis made the most conservative assumption that any tsunami could coincide with the highest possible tides. The tsunami elevations around the coast were compared against 50 year and 100 year return period extreme sea levels. Only the south west coast of the UK was found to incur sea level elevations slightly in excess of the 1 in 100 year extreme sea level predictions (and it should be noted that the default standard for coastal engineering is the 200 year return period). A further assessment of hazard reviewed the wave elevation and flow velocity at the still water level for the tsunami wave as it ran up and down typical beaches. The hazard for beaches for the hypothetical North Sea tsunami was classified as low, but the hazard for beaches in Cornwall and Devon was classified as dangerous for a **M**8.7 Lisbon 1755 type tsunami.

80. The importance of landslide generated tsunami on UK coasts is unclear. Much interest surrounds the tsunami generated by the Storegga Slide - a submarine landslide, or submarine mass failure, that occurred approximately 8200 years ago on the Norwegian continental shelf and slope. The portion of seafloor that fractured and moved downslope was approximately 200 miles wide, up to 3200 km^3 and affected an area of sea floor of 95,000 km^2.

81. Mapping of tsunami deposits show that this landslide generated a tsunami that reached the northern UK coastline. To date, evidence for the tsunami has been identified at over 30 sites from northern Scotland to north-eastern England (e.g. Smith et al., 2004). Measurements of the sediment run-up of the tsunami on the mainland Scottish coast range from 0-6 m locally above the contemporary shoreline, and up to tens of metres on Shetland, but actual water depths in which the sediments accumulated were several metres higher (Smith et al., 2007). Other possible tsunamis are registered on Shetland and dated at c. 5500 years ago and c.1500 years ago (Bondevik et al., 2005a; 2005b), but their singularity on Shetland alone renders them uncertain (Long and Wilson, 2007; Tappin et al., 2015). Thus so far, the Storegga Slide tsunami is the only landslide generated tsunami confirmed to have occurred on UK coasts.

82. The Storegga slide is of course only one of several slides along the continental slope west of the UK and Norway, most of which occurred in glacial sediments, but the frequency of sliding is as yet unclear. Neither is it clear if any of the other slides generated tsunamis which reached the UK. Ongoing research as part of the NERC (Natural Environment Research Council) funded Arctic Hazards programme of the Landslide-Tsunami Consortium is attempting to quantify the recurrence likelihood of landslide generated tsunami and their potential hazard (Landslide-Tsunami Consortium 2018).

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