Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies

Volume 6:

Coastal Flooding

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This document forms part of the Energy Technologies Institute (ETI) project 'Low Carbon Electricity Generation Technologies: Review of Natural Hazards', funded by the ETI and led in delivery by the EDF Energy R&D UK Centre. The aim of the project has been to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impact that natural hazards may have on new and existing infrastructure. This work is seen as vital given the drive to build new energy infrastructure and extend the life of current assets against the backdrop of increased exposure to a variety of natural hazards and the potential impact that climate change may have on the magnitude and frequency of these hazards.

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the ETI and authored by EDF Energy R&D UK Centre, with the Met Office and Mott MacDonald Limited. The ETI was active from 2007 to 2019, but to make the project outputs available to industry, organisations and individuals, the ETI has provided a licence to the Institution of Mechanical Engineers and Institution of Chemical Engineers to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The technical volumes outline the latest science in the field of natural hazard characterisation and are supported by case studies that illustrate how these approaches can be used to better understand the risks posed to UK infrastructure projects. The documents presented are split into a set of eleven technical volumes and five case studies.

Each technical volume aims to provide an overview of the latest science available to characterise the natural hazard under consideration within the specific volume. This includes a description of the phenomena related to a natural hazard, the data and methodologies that can be used to characterise the hazard, the regulatory context and emerging trends. These documents are aimed at the technical end-user with some prior knowledge of natural hazards and their potential impacts on infrastructure, who wishes to know more about the natural hazards and the methods that lie behind the values that are often quoted in guideline and standards documents. The volumes are not intended to be exhaustive and it is acknowledged that other approaches may be available to characterise a hazard. It has also not been the intention of the project to produce a set of standard engineering 'guidelines' (i.e. a step-by-step 'how to' guide for each hazard) since the specific hazards and levels of interest will vary widely depending on the infrastructure being built and where it is being built. For any energy-related projects affected by natural hazards, it is recommended that additional site- and infrastructure-specific analyses be undertaken by professionals. However, the approaches outlined aim to provide a summary of methods available for each hazard across the energy industry. General advice on regulation and emerging trends are provided for each hazard as context, but again it is advised that end-users investigate in further detail for the latest developments relating to the hazard, technology, project and site of interest.

The case studies aim to illustrate how the approaches outlined in the technical volumes could be applied at a site to characterise a specific set of natural hazards. These documents are aimed at the less technical end-user who wants an illustration of the factors that need to be accounted for when characterising natural hazards at a site where there is new or existing infrastructure. The case studies have been chosen to illustrate several different locations around the UK with different types of site (e.g. offshore, onshore coastal site, onshore river site, etc.). Each of the natural hazards developed in the volumes has been illustrated for at least one of the case study locations. For the sake of expediency, only a small subset of all hazards has been illustrated at each site. However, it is noted that each case study site would require additional analysis for other natural hazards. Each case study should be seen as illustrative of the methods outlined in the technical volumes and the values derived at any site should not be directly used to provide site-specific values for any type of safety analysis. It is a project recommendation that detailed site-specific analysis should be undertaken by professionals when analysing the safety and operational performance of new or existing infrastructure. The case studies seek only to provide engineers and end-users with a better understanding of this type of analysis.

Whilst the requirements of specific legislation for a sub-sector of energy industry (e.g. nuclear, offshore) will take precedence, as outlined above, a more rounded understanding of hazard characterisation can be achieved by looking at the information provided in the technical volumes and case studies together. For the less technical end-user this may involve starting with a case study and then moving to the technical volume for additional detail, whereas the more technical end-user may jump straight to the volume and then cross-reference with the case study for an illustration of how to apply these methodologies at a specific site. The documents have been designed to fit together in either way and the choice is up to the end-user.

The documents should be referenced in the following way (examples given for a technical volume and case study):

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Volume 1 – Introduction to the Technical Volumes and Case Studies. IMechE, IChemE.

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Case Study 1 – Trawsfynydd. IMechE, IChemE.

Contents

1. Introduction

Coastal flooding is a natural phenomenon which is capable of devastating coastal towns, infrastructure, and regional economies. The focus of this technical volume is to provide some basic knowledge and to present some of the available tools that are used to assess the coastal flood risk. This technical volume can assist users in the development and implementation of resilient solutions, systems, structures, and plant and assist with effective management of the natural hazard risks caused by coastal flooding.

The UK has a long coastline of approximately 12,500 km. The length around mainland Britain (excluding the other British islands) is 8000 km (*Zsamboky et al., 2011*). The UK coastline is one of the longest in Europe and is constantly evolving and shifting over time. It is varied in geography and habitats. The coastline is relatively easily accessible to the UK population; nowhere in the UK is more than 120 km from the coast.

A single coastal flooding event can have a widespread impact. UK coastal flooding records date back to 1099. On the east coast of mainland Britain thousands of people were drowned due to coastal flooding events in 1099, 1146 and 1421 (*Gönnert et al., 2001; Haigh et al., 2016*). In the last 500 years major coastal flood events have had an impact on the UK coast which resulted in the deaths of up to thousands of people, including events in 1607, 1703, 1824, 1928, 1953 and 2013/14 (*Haigh et al., 2016*). The 1607 flood remains the event that has caused the greatest loss of life from any sudden-onset of natural catastrophe in the UK over the last 500 years (*RMS, 2007*). In many historic events the impact of flooding was exacerbated by poorly managed, failure of and absence of flood defences. By the end of World War II the UK's coastal flood defences were in a very neglected state (*Kraus, 1996*). The Great North Sea Flood (in 1953) highlighted the inadequacy of coastal defences in place in the UK at that time. It caused an estimated 2000 breaches in the natural and artificial flood defences (*Muir-Wood et al., 2005; Cooling and Marsland, 1954*).

The most destructive coastal surge storm event in living memory in the UK was the infamous 1953 North Sea flood. It was caused by a serious storm that occurred on the night of Saturday 31st January 1953 and the morning of 1st February 1953. Severe floods struck the UK, the Netherlands and Belgium (*McRobie et al., 2005*). A combination of wind, high tide and low pressure led to a water level of more than 5.6 metres (m) above mean sea level in places. The flood and waves overwhelmed sea defences and caused extensive flooding. England suffered one of the biggest environmental disasters to have ever occurred in this country. Flood defences were breached by a combination of high tides, storm surge and large waves. Over 600 km^2 of land was flooded, 307 people killed and 200 industrial facilities were damaged by floodwater. A month after the flooding, the estimated cost was £40 to £50 million, the equivalent of around £1.2 billion in 2018, not including the cost of relocation and interruption of business activity.

Stormy weather experienced across the UK from late October 2013 through to February 2014 resulted in several coastal flooding incidents. The worst tidal surge in 60 years was experienced on England's east coast, leading to 2800 homes being flooded, significant coastal erosion and a need to evacuate thousands of people to safety. The tidal surge events that occurred on 5th/6th December 2013 had a record water level of 5.8 m above the *ordnance datum** near Hull along the Humber Estuary on the east coast. Further flooding occurred in early January 2014 when coastal areas — particularly in Wales, Devon and Cornwall — were battered by a combination of rain, the highest waves in 30 years and strong winds. Another storm in February led to further significant damage in this part of the UK, with thousands left without power, and a section of sea wall and a 100 m stretch of railway destroyed in the coastal town of Dawlish. Fortunately, with vastly improved infrastructure, forecasting and response, the loss of life was nothing like that experienced 60 years ago (*Thorne, 2014; Kendon and McCarthy, 2015*), but the damage was nevertheless extensive and quite unlike what many have seen before in their lifetimes.

National legislation is aimed at providing better, more sustainable, management of flood and coastal risks for people, homes, businesses and the environment. The Pitt Review (*Pitt, 2008*) looked at lessons learned from the widespread flooding in 2007. The Government's response to the Pitt Review led to development of the Flood and Water Management Act 2010. The two most important legislative acts associated with coastal flooding are: i) The Coast Protection Act 1949 — the key legislation for matters relating to coastal erosion risk on the open coast; ii) The Flood and Water Management Act 2010 — this updates previous legislation, including the Coast Protection Act 1949, and clarifies responsibilities on the coast for both flooding and erosion.

*All technical terms marked in blue can be found in the Glossary section.

Coastal flooding is defined as an event when the land along the coast is inundated by seawater above normal tidal conditions. The extent of coastal flooding is influenced by the coastal floodplain topography exposed to flooding, with the slope of the land adjacent to the coast playing an important part. Seawater will more easily propagate on a flat coast than on a steep one where land rapidly rises away from the sea.

Coastal flooding is normally caused by a combination of **high tides**, **storm surges**, and **waves**. *Figure 1* illustrates the characterisation of coastal flooding.

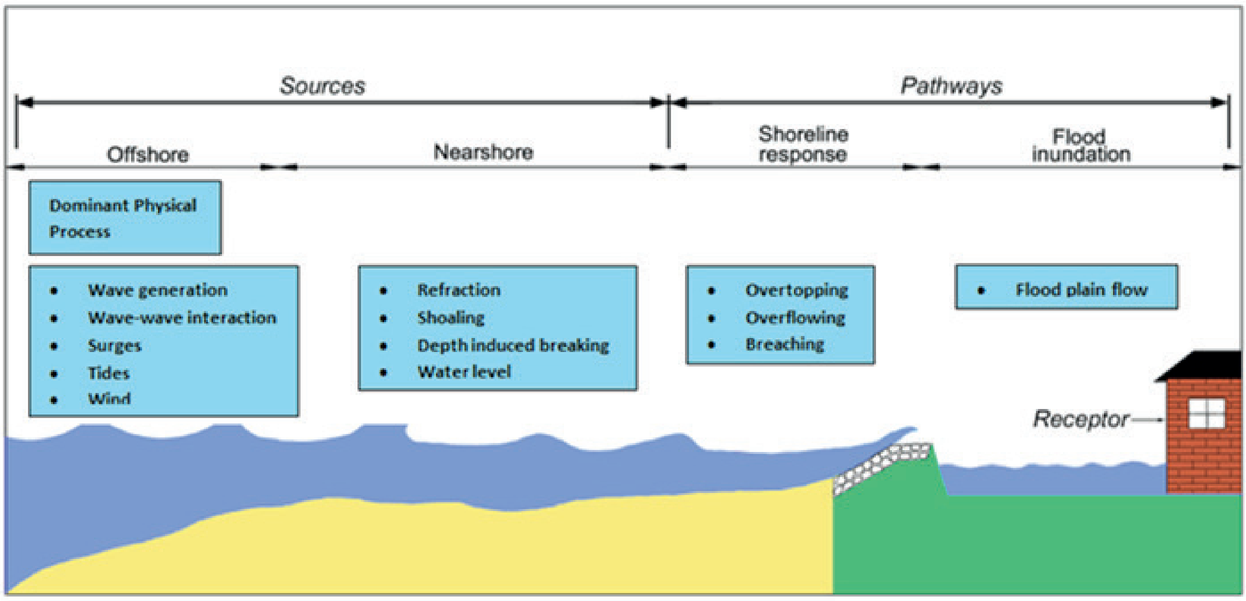

Figure 1. Characterisation of coastal flooding mechanisms (Source – Pathway – Receptor). (Source: Defra/EA, 2004)

High tides generally occur once every 12 hours and 25 minutes, although regional variations are possible. There are two special tides known as spring tides and neap tides as shown in *Figure 2*.

Spring tides occur when the Sun, the Earth and the Moon are aligned (see *Figure 3*). They happen just after a new or full Moon, when there is the greatest difference between high and low water. Spring tides have nothing to do with the season of spring. They occur once every two weeks, i.e. half of a lunar month (the time it takes the Moon to orbit the Earth once) which is 28 days. Spring tides are much higher than normal tides and can contribute greatly to coastal flooding.

Neap tides happen seven days after a spring tide. They refer to a period of moderate tides when the Sun, Earth and Moon are at right angles to each other (see *Figure 3*). A neap tide occurs when the difference between high and low tide is least. Neap tides occur twice a month, in the first and third quarters of the Moon. Neap tides are lower than normal tides and thus are of less concern in relation to coastal flooding.

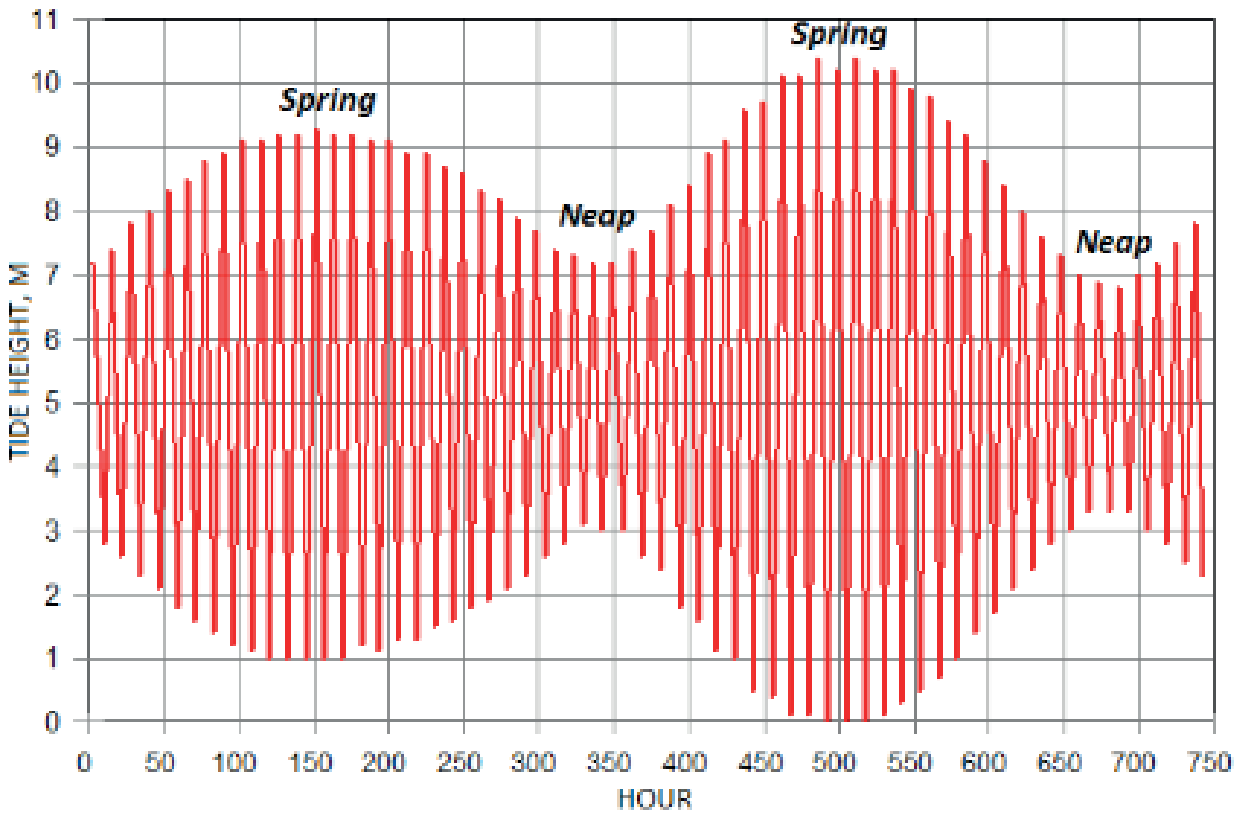

Figure 2. Example of a typical semi-diurnal spring tide and neap tide. (Source: Mott MacDonald)

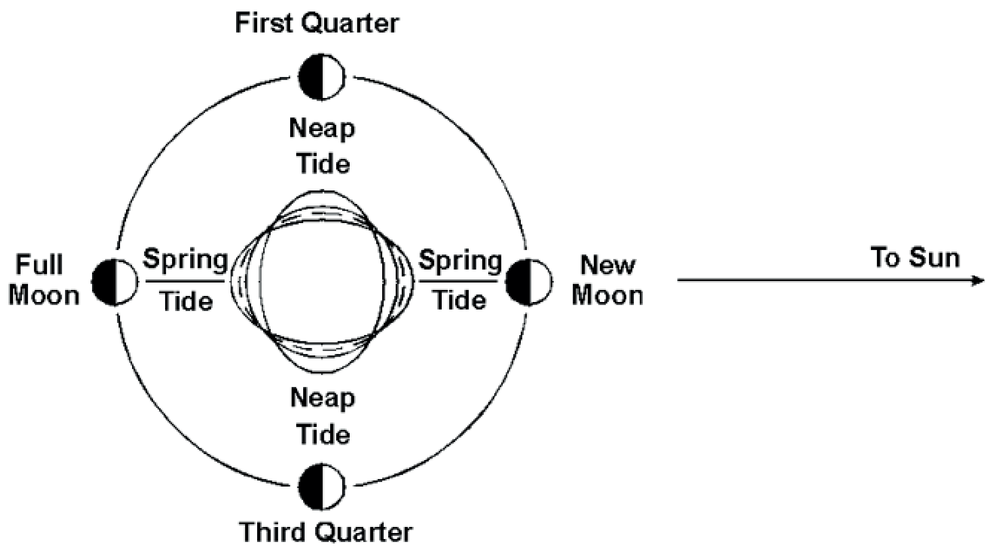

Figure 3. Diagram showing Sun, Earth, and Moon positions for spring tides and neap tides. (Source: Mott MacDonald)

Storm surges are rapid and transient rises in sea level caused by very strong winds, normally those found in hurricanes and cyclones. The strong winds push the water on the ocean's surface on top of the existing water level, increasing the sea level. Another factor contributing to storm surge is atmospheric pressure. The conditions needed to create these strong winds are generally associated with low air pressures; this leads to the increase in sea level. During a cyclone, the pressure is higher at the edge than it is at the centre. This pushes down the water in the outer parts of the storm, causing the water to bulge at the centre, where the winds have helped add to the rise in the sea level. Storm surges are most dangerous during high tides as at these times the sea level will already be elevated. The water level can reach several metres in height if the storm surge happens at the same time as high tide, and can increase yet further if it coincides with spring tide.

Waves result from the wind blowing over the surface of the sea. The wave height is affected by the wind speed, wind duration, fetch length (distance of wind travel over open water), depth of water, roughness of the sea bed, and direction and speed of the tide. In stormy conditions, the strong winds associated with the storm generate large and powerful waves on top of the surge, which can cause damage to coastal defences, cause breaches of the defences, and/or overtop the coastal defences (*Figure 4*). In cases worse than these, flooding of the land behind the defences may occur. When the waves enter shallow water their speed decreases, wavelength decreases, and height increases. Tide direction against the wind will also increase wave height and decrease wavelength. Strong wind blowing towards the land will impose greater risk of coastal flooding than if the wind is blowing away from the land towards the sea. If the wave breaks in the nearshore shallow water zone the wave height will be limited.

Shallow estuaries and harbours can experience large waves during a strong onshore wind, particularly if these coincide with a spring ebb tide. The 1953 coastal flood along the east coast was exacerbated by the narrowing of the sea towards the English Channel; the excess water from the storm was forced into the narrow English Channel raising its level. Tidal bores are also possible on some estuaries and can result in flooding.

Coastal flooding can also be caused by tsunamis. Tsunamis are waves resulting from any sort of major displacement of water in the ocean such as earthquakes, volcanic eruptions, submarine landslides or meteorite impacts. Tsunamis are very dangerous as they travel quickly and are difficult to detect. However, tsunamis affecting the British Isles are extremely uncommon, and there have only been two confirmed cases in recorded history. One event occurred around 6100 BC. The east coast of Scotland was struck by a 70 feet (21 m) high tsunami during this event.

The wave was caused by the massive Storegga submarine landslide off Norway. In November 1755, the coast of Cornwall was hit by a 3 m high tsunami. The waves were caused by the 1755 Lisbon earthquake. Meteotsunamis (tsunami-like waves of meteorological origin) are somewhat more common, especially on the southern coasts of England around the English and Bristol Channels.

In the UK, the east coast is at a particularly high risk of flooding because the sea is rising and the land is sinking, especially along the southern part of the east coast. The geology along this part of the east coast is also less resistant to erosion. This results in more coastal flooding and erosion along this part of the coastline. This is of concern as there are many people living along the east coast and there are also many power plants situated along this coast, with four of them being nuclear power plants (there are also two nuclear plants which are in a decommissioning phase).

Figure 4. Wave overtopping coastal flood defence at Dawlish, Devon. (Source: Shutter Stock)

Coastal flooding is influenced by a combination of tide, surge and waves. It is useful to know how these key components are measured and predicted, and what techniques and tools are available, so as to have a better understanding of the coastal flooding risk and effectively manage the risk.

3.1 Observation and measurement of tide and surge

Sea level is measured using a tide gauge, which is a device to measure the changes in sea levels relative to a datum. There is a network of tide gauges installed along the UK coastline. There are several types of tide gauge which have been developed over time with advancing technology. These include: full-tide bubbler, half-tide bubbler and direct pressure transducer systems. The UK Tide Gauge Network (UKTGN) and its data (*NOC, 2018a*) are the responsibility of the Environment Agency (EA). Since April 2016, the network is maintained by EA and its contractors. *NOC (2018a)* also provides the real-time operational status of the instruments, tide gauges and system.

The UK Tide Gauge Network is part of the National Tidal and Sea Level Facility (NTSLF). It records tide elevations at 44 locations around the UK coast as shown in *Figure 5*. It was set up in response to severe flooding along the east coast of England in 1953. It forms part of the UK Coastal Flood Forecasting (UKCFF).

Admiralty EasyTide, from the United Kingdom Hydrographic Office (UKHO), is a web-based tidal prediction service. The service provides tidal data for over 7000 ports worldwide together with a host of other useful information. EasyTide enables the user to select any date for the prediction between 100 AD and up to 50 years in the future, and it is possible to access tide predictions for 7 or 14 days at a time.

3.2 Forecasting of storm surge

Storm surges are water movements caused by meteorological effects such as winds and atmospheric pressure changes. It requires powerful computers and sophisticated software to predict a storm surge and the prediction is only possible up to two days in advance of the event.

The NTSLF at the National Oceanography Centre (NOC) develops and maintains tide-surge models for EA. These models are used for forecasting storm surges on the coasts of England and Wales. Tide-surge models are run in real-time as part of the forecast suite of models at the Met Office. Results are used by the UK Coastal Monitoring and Forecasting Services (UKCMF) and transmitted to EA. EA uses the results, together with data from the UKTGN, for generating coastal flood warnings in England and Wales.

The present system comprises a 12 km shelf model (CS3X). The modelled surge is combined with tides predicted at tide gauge sites to give the best estimate of the total water level.

These models run on supercomputers at the Met Office. They are a critical part of today's coastal flood warning system in the UK. The system also makes use of a technique called ensemble forecasting to quantify the inherent uncertainty in short-term weather prediction. Multiple runs are made, adjusting model conditions and parameters, to provide a range of outcomes that can then be used to judge the reliability of the forecast.

Figure 5. Tide gauge locations for the UK tide gauge network. (Source: Mott MacDonald (contains Ordnance Survey data Crown copyright database right © 2018))

The NTSLF at the NOC operates the network of 44 stations on behalf of EA, the Scottish Environment Protection Agency (SEPA) and others; logging and telemetry systems transfer data to the Met Office and then to EA in near real-time. The data are also quality controlled and archived by the British Oceanographic Data Centre (BODC) at the NOC.

Surge forecasts for the next 48 hours, from the NOC's storm surge model run at the Met Office, can be viewed online (*NOC, 2018b*). *Figure 6* shows the schematic diagram of the current, as of February 2018, surge forecast and flood warning system in the UK.

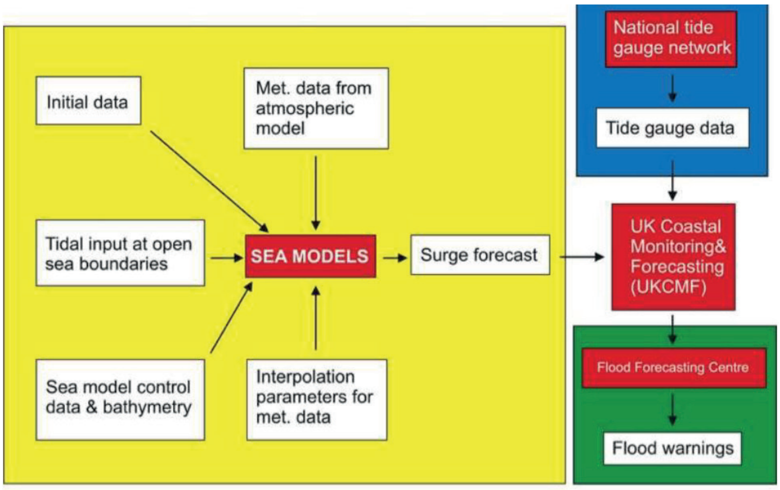

Figure 6. Storm surge model structure at the NOC: the current surge forecast and flood warning system. (Source: National Oceanography Centre)

Forecasts and archived forecasts of storm surges are given for 35 coastal sites around the UK coastline at NTSLF's website (*NOC, 2018b*).

Although CS3X is an effective model, it has limited development opportunities. The NOC and the Met Office are collaborating on developing a Nucleus for European Modelling of the Ocean (NEMO) based 2D surge model. The 2D depth-averaged tidal NEMO-surge configuration, with horizontal resolution of 7 km using European Marine Observation and Data Network (EMODnet) *bathymetry*, gives good results in terms of *harmonic tidal constituents* derived at UK Class A tide gauges when compared to observations. The results are comparable to, if not better than, tide only runs of the operational surge model CS3X.

3.3 Monitoring and forecasting of waves

WaveNet, the Centre for Environment, Fisheries and Aquaculture Science's (Cefas) strategic wave monitoring network for the UK, provides a single source of real-time wave data from a network of wave buoys located in areas at risk from flooding. In operation since 2002, WaveNet collects and processes data from the Cefas-operated Datawell Directional Waverider buoys. 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 (*Cefas, 2018*). The WaveNet interactive map shown in *Figure 7* gives a clear picture of the wave conditions in terms of direction and magnitude along the coastline at a glance.

Cefas sends the wave data to the Met Office (to help improve the wave and tidal surge model) and to the National Flood Forecasting Service for access by the UKCFF. Regional flood forecasters, local authorities and other stakeholders use the near real-time data from the buoys and the model predictions to provide better advice, guidance and warnings to emergency responders and communities about imminent coastal flood risk.

The Met Office plays an important part in developing and maintaining global, regional, and coastal wave forecast models to forecast the sea-state. Model configurations are based upon the National Centers for Environmental Prediction (NCEP) community model WAVEWATCH III. WAVEWATCH III is the third-generation wind and wave model produced by NCEP. The model uses more sophisticated mathematical equations and physics than its predecessors and is run four times a day. WAVEWATCH III is evolving from a wave model into a wave modelling framework, which allows for easy development of additional physical and numerical approaches to wave modelling.

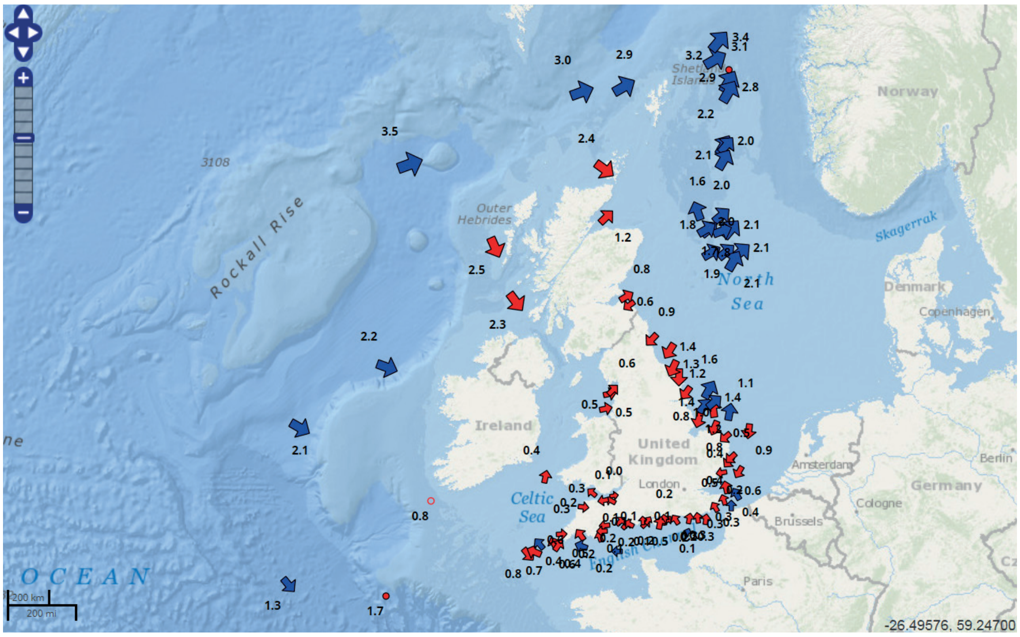

Figure 7. WaveNet interactive map. Red arrows indicate wave direction and the associated value indicates significant wave height, blue arrows indicate wind direction and the associated value indicates significant wave height. (Source: Cefas, 2018)

3.4 Coastal erosion

Recession of coastal land is often caused by erosion from the sea acting together with landslides caused by interactions between groundwater and the soil or rock. Coastal erosion occurs along different parts of the UK coastline (see *Table 1*). EA has produced an Erosion Zone map which is available on its website (*EA, 2017a*).

Table 1. Coastal erosion and protection in the UK (Eurosion, 2004). Islands with a surface area smaller than 1 km² and inland shores where the mouth is less than 1 km wide are not included. (Source: Masselink and Russell, 2009)

Region	Coast length	Coast length which is eroding		Coast length with defence works and artificial beaches	
	km	km	%	km	%
North East England	297	80	26.9	111	37.4
North West England	659	122	18.5	329	49.9
Yorkshire and Humber	361	203	56.2	156	43.2
East Midlands	234	21	9.0	234	99.8
East England	555	168	30.3	382	68.8
South East England	788	244	31.0	429	54.4
South West England	1379	437	31.7	306	22.2
England	4273	1275	29.8	1947	45.6
Wales	1498	346	23.1	415	27.7
Scotland	11,154	1298	11.6	733	6.6
Northern Ireland	456	89	19.5	90	19.7
UK	17,381	3008	17.3	3185	18.3

Where coastal erosion is known to be occurring, some predictions have been made based on historical evidence, ongoing monitoring and other data, to estimate where the shoreline position will be at a certain time.

The 'erosion zone' is the area of land predicted to be at risk from coastal erosion over a defined period of time — not the area that will definitely be lost. The predicted extent of this zone is shown under the heading 'coast length which is eroding' in the results table (*Table 1*).

The annual rate of erosion at a point along the shoreline is often unpredictable. Erosion often happens as a single event at a particular place rather than in a steady, uniform manner.

Instead of showing erosion rates, EA's website provides the erosion zone predicted over three timescales — from 2010 (when this data was developed) up to about 2030, up to about 2060 and up to about 2110. It is shown as a range (e.g. '0.5 to 3.2 metres') that represents the upper and lower limits of the erosion we should reasonably expect to see by that time. On EA's website, the predicted erosion zone considers the impact and likelihood of landslides.

Note that where no erosion predictions are shown because there is an aspiration to build or maintain defences (in other words where the policy is to hold existing defence line), there may still be risks from landslides occurring behind those defences.

Predicting coastal erosion is an uncertain science. However, long-term predictions are required for planning coastal flood management into the future. Coastal erosion should be taken into consideration in assessing coastal flood risk and building future resilience.

3.5 Coastal flooding database

The University of Southampton, the NOC, and the BODC created a 100-year database (see *Figure 8*) of coastal flooding in the UK, called SurgeWatch (*University of Southampton, 2018*). The 96 largest events over this period were compiled, with information on the storm that generated each event, the high-water levels recorded during the events, and the severity of coastal flooding. *Figure 8* shows the magnitudes of the 96 largest coastal flooding events that have occurred along the UK coastline. This historical record will be a useful source when making comparison of future events to historical events.

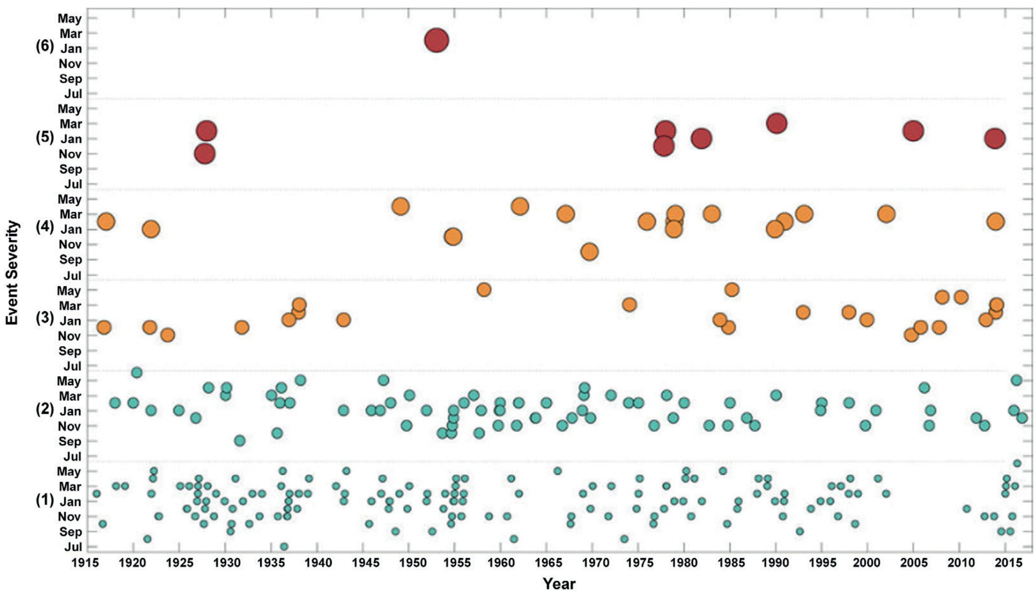

Figure 8. UK historical coastal flooding events; ranking of severity of flooding is shown qualitatively in scale 1 to 6 on the y-axis for all these flood events; 6 in the y-axis represents the worst event; additional information is also attached to y-axis on the name of months the events happened. (Source: University of Southampton, 2018)

In order to assess hazards from coastal flooding, it is necessary to know about the likelihood of the hazard occurring and the severity/consequence of the event should it happen. In this section, the different appropriate methodologies used to obtain these risk estimates are outlined.

Flood risk mapping and flood forecasting are the key tools for managing flood hazards. This section provides key methodologies for estimating coastal flood risk and coastal flood risk mapping:

- horizontal projection method for flood risk mapping using extreme sea levels from EA's Coastal Flood Boundary (CFB) dataset (*EA, 2016a*) and ground elevation from a digital terrain model (DTM);
- numerical modelling for flood risk mapping;
- numerical modelling for flood forecasting.

Lists of the data used for preparation of coastal flood risk models, maps, and flood forecasting models are presented in *Table 2*. The section also presents methods for derivation and usage of the key data.

Table 2. Requirement of data input for preparation of coastal flood risk map. (Source: Mott MacDonald)

Data	Description	Usage
Coastal Flood Boundary dataset	The "Coastal flood boundary conditions for the UK mainland and islands" (CFB project) was undertaken as part of the joint Environment Agency/ Department for Environment, Food and Rural Affairs (EA/Defra) Flood and Coastal Risk Research and Development Programme. Extreme sea levels are available from 1 in 1 year to 1 in 10,000 year return period; available at about 2 km intervals across the coast accurate up to 1 decimal, represents still water condition including effect of surge, but does not include localised effect, such as effect of wave set-up. This dataset does not cover estuaries, sea lochs or firths.	Provides predicted sea levels for much of the UK coastline, determines where additional sea level points were required; infers confidence levels for new sea level points.
Tide gauge data	Observed sea level data from the tide gauges maintained by EA at 44 locations along the UK's coastline and also from other tide gauges owned by other organisations such as SEPA, Port of London Authority (PLA); EasyTide also has a network of many tidal gauges along the coast and ports of the UK.	Provides sea levels for statistical analysis, trend analysis, comparison, filling data gaps and prediction of future sea levels.
Digital Terrain Model	The DTM comprises mainly high resolution LiDAR up to 50 cm horizontal resolution and also DTM from other satellite source (e.g. Intermap's NEXTMap DTM, Shuttle Radar Topography Mission (SRTM) etc.) and bathymetric data.	Used to develop numerical model for flood mapping.
Flood Risk Management (FRM), Strategic Flood Risk Management (SFRM), modelling studies by EA, SEPA and local authorities	Detailed local assessments of flood risk providing numerical models to cover specific areas.	Provides sea levels and flood extents not covered by CFB in horizontal projection method.
Flood defence asset database	Detailed information on flood protection schemes and associated assets.	Used in numerical model, in CFB to assess its effect and delineate areas benefitting flood risk.
Local authority defence and structure information	Information on hydraulic structures and defences in their areas where available, for example as built drawings or flood defence scheme reports.	Used in numerical model, check for flow control.
Sea level rise	Projections of sea level rise around the coastline taken from the UK climate projection (UKCP09) and future update when becomes available.	To obtain climate change uplifts along coastline for floods with varied likelihoods of occurrence return period sea levels (UKCP18; *EA, 2016b*).

4.1 Horizontal projection method for flood risk mapping

One of the methods for coastal flood risk mapping is to use the horizontal projection method; the CFB dataset for the UK mainland and islands and DTM are the two inputs for preparing maps. This kind of map is produced as a strategic product to support flood risk management (FRM) at community level.

This approach identifies all the land at a lower elevation than the CFB sea levels, or derived sea levels, for each return period as being at risk of flooding. Sea level grids, depth grids and flood extents are produced for eight scenarios (10, 25, 50, 100, 200, 200 plus climate change, 1000 and 10,000-year return periods).

There are a number of limitations in this method:

- cannot account for impacts by *wave overtopping*;
- cannot account for influence of existing flood defence and thus areas benefitting from flood defence cannot be mapped;
- does not consider volume of water to inundate areas and thus can over-estimate flooding in areas of wide and flat terrain;
- as it cannot account for wave overtopping, the flooding may be under-estimated in areas exposed to wave-actions.

As horizontal projection modelling cannot consider the effect of flood defence, it generates a flood map for the undefended scenario. Formal flood defence information can be obtained from EA's Asset Information Management System (AIMS) database, and the Scottish Flood Defence Asset Database (SFDAD).

Natural Resources Wales has good asset information and arrangements (*Auditor General for Wales, 2016*) in place to inspect its assets; this information can be obtained through formal request.

The flood maps derived from this method are of a strategic nature to support flood risk management planning at a community level. They are not appropriate for use to assess site-specific flood risk. These maps form a key basis for FRM Planning and support decision-making for FRM Strategies and Local FRM Plans. The maps are not licensed for commercial use and all users must agree to terms and conditions before viewing the map.

4.2 Numerical modelling for flood risk mapping

At the regional scale, hydrodynamic modelling is the state-of-art approach for developing consistent and complete sea level data that can be applied to flood risk assessments. As the modelling of surges in shallow coastal areas requires a high resolution, such a modelling approach has generally been computationally too costly to apply on the global scale. The application of unstructured grids (or a 'flexible mesh') in hydrodynamic models makes it possible to have a sufficient resolution in shallow coastal areas while maintaining computational efficiency. These developments in hydrodynamic modelling, combined with the increasing availability of global datasets on climate and elevation, make it possible to upscale the hydrodynamic modelling to the global scale.

Assessing the flood risk along the coastal floodplain involves three key steps:

- Step 1: assess the risk from the source — e.g. estimating the magnitude of tide, surge and wave as illustrated in *Section 3*.
- Step 2: assess the risk from the pathway — e.g. the overtopping rate, outflanking and locations of coastal defences, their present condition, and their erosion vulnerability. One of the tools that is used widely by researchers and practitioners for calculating the wave overtopping rate is EurOtop (*EurOtop, 2016*).
- Step 3: assess the risk (including flood hazard, velocity, depth, extent and duration) at the receptor — e.g. inundation modelling of coastal floodplain resulting from the seawater overtopping the coastal defences.

4.3 Coastal flood forecasting

EA operates a flood warning service across much of England and Wales under Section 166 of the Water Resources Act, 1991 (*EA, 2010*).

There remains a residual risk that overtopping will occur under certain circumstances even in areas with flood defences. In light of this knowledge, Flood Forecasting Warning and Response (FFW&R) manages these residual flood risks as well. FFW&R can inform decisions related to the areas most likely to flood, defence lengths most likely to breach, number of people in danger, vulnerability of the endangered people, extent of likely damage to property, extent of impact of individual failed defences on the number of people in danger, extent of impact of individual failed defences on the likely extent of damage to property, and the most beneficial areas to target emergency resources.

Comprehensive flood forecasting systems can provide information on all aspects of the

Source-Pathways-Response and Consequence model (S-P-R-C, see *Figure 1*). The approach of forecast modelling differs depending on complexities, and thus forecast models are developed in four categories as recommended in EA's best practice modelling guidelines (*Defra/EA, 2004*):

- offshore models;
- nearshore models;
- shoreline response models;
- flood inundation models.

The forecast variables/outputs from these models are: wind conditions, wave conditions, water levels, overtopping rates, breach likelihood, flood depths and velocity, extent of flooded area, potential damage, potential for loss of life.

The current National Flood Forecasting System (NFFS) came into operation in 2004 and provides flood forecasts for England and Wales. The NFFS uses data from the Met Office and the Flood Forecasting Centre (FFC) before running the data through modelling software to provide accurate future flood forecasts. It has been recognised that the NFFS is now out of step with EA's organisational model. EA is continually looking at new ways to improve the national flood forecasting and warning system. Currently, a new replacement system called the Future Flood Forecasting System (FFFS) is being developed by EA.

4.4 Extreme sea levels (Coastal Flood Boundary data)

Practical guidance for design with consideration of extreme sea levels along the UK coast was published in 2011 by EA (*EA, 2011*). It provides CFB data for the UK mainland and islands. The key outputs from that R&D project include:

- A consistent set of extreme peak sea levels of annual exceedance probability (AEP) ranging from 100 to 0.01 per cent (return period of one year to 10,000 years).
- Peak sea level values along the coastline at a spacing of about two kilometres. This enables rapid selection and interpolation of appropriate levels.
- Advice on generating an appropriate total storm tide curve for use with extreme sea levels. Standard surge tide shapes are given for each part of the coast.

The metadata record is published by EA, licensed under Open Government Licence (OGL). Tide gauge locations are part of Coastal Design/Extreme Sea Levels, a GIS dataset and supporting information which provides design/extreme sea level and typical surge information for around the coastline of England and Wales under present-day conditions. Data for Scotland are available from SEPA. This is a specialist dataset which informs on work ranging from coastal flood modelling, scheme design, strategic planning, and flood risk assessments.

The surge shape needs to be combined with an astronomical tide to give the total storm tide curve. The results are available in GIS format (shapefiles). They can be obtained from EA on request.

The 2011 CFB dataset has been updated using the most current techniques. New CFB data are likely to be available soon (as of publication of this technical volume in late 2018).

4.5 Extreme waves (State of the Nation)

EA has carried out a study on the State of the Nation (SoN) Flood Risk Analysis along the coastline of England. The outputs from this study include wave heights and wave periods for the English coast. The report on the coastal element of SoN is freely available to all on request from EA. The wave heights for a wide range of tidal events at different AEPs ranging from 100 to 0.01 per cent AEPs are available on request. The report has not been published at the time of writing of this document.

4.6 Climate change allowance

The UK Government has published guidance on climate change allowances for flood risk assessments (*EA, 2017b*). This guidance sets out when and how to use climate change allowances in flood risk assessments and strategic flood risk assessments.

The National Planning Policy Framework (NPPF) sets out how the planning system should help to minimise vulnerability and provide resilience to the impacts of climate change. Making an allowance for climate change in flood risk assessment will help to minimise vulnerability and provide resilience to flooding and coastal change in the future.

The climate change allowances are predictions of anticipated change for:

- peak river flow by river basin district;
- peak rainfall intensity;
- sea level rise;
- offshore wind speed and extreme wave height.

The allowances are based on climate change projections with different scenarios of carbon dioxide (CO_2) emissions to the atmosphere. There are different allowances for different epochs or periods of time over the next century.

The range of allowances is based on percentiles. A percentile is a measure used in statistics to describe the proportion of possible scenarios that fall below an allowance level. The 50th percentile is the point at which half of the possible scenarios for peak flows fall below it and half fall above it (i.e. the median value). The:

- central allowance is based on the 50th percentile;
- higher central is based on the 70th percentile;
- upper end is based on the 90th percentile.

The climate change allowance which should be used is dependent upon the type of development and the flood zone in which it will be located. The requirements are set by the Government and are summarised in *Table 3*.

Table 3. Environment Agency's flood zone and climate change allowance as per 2017 guidance (EA, 2017b).

Flood zone	Climate change allowance
Zone 1 Low Probability	• Essential infrastructure – use the central allowance • Highly vulnerable – use the central allowance • More vulnerable – use the central allowance • Less vulnerable – use the central allowance • Water compatible – use none of the allowance
Zone 2 Medium Probability	• Essential infrastructure – use the higher central and upper end to assess a range of allowances • Highly vulnerable – use the higher central and upper end to assess a range of allowances • More vulnerable – use the central and higher central to assess a range of allowances • Less vulnerable – use the central allowance • Water compatible – use none of the allowances
Zone 3a High Probability	• Essential infrastructure – use the upper end allowance • Highly vulnerable – development should not be permitted • More vulnerable – use the higher central and upper end to assess a range of allowances • Less vulnerable – use the central and higher central to assess a range of allowances • Water compatible – use the central allowance
Zone 3b The Functional Floodplain	• Essential infrastructure – use the upper end allowance • Highly vulnerable – development should not be permitted • More vulnerable – development should not be permitted • Less vulnerable – development should not be permitted • Water compatible – use the central allowance

Notes:
- *These flood zones refer to the probability of rivers and sea flooding, ignoring the presence of defences.*
- *The definitions of the flood zones are provided in Table 4 of this technical volume.*
- *If (exceptionally) development is considered appropriate when not in accordance with flood zone vulnerability categories, then it would be appropriate to use the upper end allowance.*

4.7 Joint probability analysis

Due to climate change, sea level rise, increasing storminess and coastal erosion, and despite significant investment in coastal defences in the UK, coastal flooding remains a serious threat to life and national critical infrastructure as well as to economic and environmental assets.

Joint probability refers to the chance of two or more conditions occurring at the same time. Joint probability analysis takes account of the dependence between input variables as well as the distributions and extremes of the individual variables. It can increase the accuracy of impact/failure probability estimation. The most common application of joint probability methods in coastal engineering is to waves and high surge occurring near high tide for assessment of flood risk at sea defences. Traditional methods have involved the application of joint probability contours (JPC), defined in terms of extremes of the sea conditions, that can, if applied without correction factors, lead to the underestimation of flood risk and under-design of coastal structures.

Multivariable extreme value analysis such as the conditional extremes approach (*Heffernan and Tawn, 2004*) for system flood risk analysis (e.g. *Wyncoll and Gouldby, 2013*) has been commonly used for joint probability analysis of waves and water levels. The JOIN-SEA programme produced by HR Wallingford has been used widely in the UK (*HR Wallingford, 1998*).

EA led an R&D project on the spatial joint probability for flood and coastal risk management and strategic assessments. The methods report details techniques of joint probability (*Defra, 2017*). Relevant joint probability analysis tools might also be released in the near future.

Coastal flooding is related to extreme weather events (e.g. high winds/hurricanes) and seismic and geological events (e.g. earthquakes and landslides leading to tsunamis). It is not directly associated with other natural hazards such as hail and extreme rain except in that these are often experienced in conjunction with high winds. Coastal flooding is generally independent of natural hazards such as lightning, rain and river flooding. For estuaries, however, flooding could be caused by a combination of high river flows, high tide and strong wind conditions.

Growing populations in higher risk coastal areas and large cities, lifestyle and demographic changes will be key challenges in future coastal flood risk assessment. About 30% of the UK total population lives in coastal urban areas. The UK's population is projected to grow from 65.6 million in mid-2016 to 72.9 million in mid-2041. The number of elderly (aged over 85) is projected to double during the next 25 years. More vulnerable sections of the population often live near coastal towns; in historic major coastal flood events the highest loss of life was recorded among the elderly section of the population.

Given the timescale associated with climate change, society's willingness to take measures to mitigate it (e.g. energy savings and CO_2 reduction) will be a factor.

There are uncertainties in flood level prediction relating to *coastal morphodynamics*. The present practices of flood risk assessment modelling are not sediment driven, they are pure hydrodynamic modelling. Sea levels along the shoreline are critically dependent on shoreline morphodynamics. Beach erosion-deposition and the presence of sand dunes are critical to the sea levels along the coast. The Water Framework Directive (EC 2000/60/EC) lists engineering/management activities regulated with respect to sediment management; there is increased awareness that sediment controls to floodwater conveyance are important for flood risk management.

The key regulations related to development in coastal regions and coastal flood risks (*EA, 2010*) are presented in this section. Volume 1 — Introduction to the Technical Volumes and Case Studies provides information on the general approach to UK regulation regarding natural hazards. However, note that the regulations listed are by no means exhaustive. Regulations are updated and new regulations are also introduced. It is advisable to apply the most up to date.

The Conservation of Habitats and Species Regulations 2017

The regulations came into force on 30th November 2017, and extend to England and Wales (including the adjacent territorial sea) and to a limited extent in Scotland (reserved matters) and Northern Ireland (excepted matters). In Scotland, the Habitats Directive is transposed through a combination of the Habitats Regulations 2010 (in relation to reserved matters) and the Conservation (Natural Habitats, & c.) Regulations 1994. The Conservation (Natural Habitats, etc.) Regulations (Northern Ireland) 1995 (as amended) transpose the Habitats Directive in relation to Northern Ireland. The regulations provide for the designation and protection of 'European sites', the protection of 'European protected species', and the adaptation of planning and other controls for the protection of European sites.

The Environmental Permitting Regulations 2016

The new regulations came into force on 1st January 2017. Whilst there are no major changes because of the new regulations, they provide a consolidated system of environmental permitting in England and Wales and transpose provisions of fifteen EU Directives which impose obligations requiring delivery through permits or which are capable of being delivered through permits. The new regulations revoke the Environmental Permitting (England and Wales) 2007 (and amendments) as well as the Environmental Permitting (England and Wales) Regulations 2010.

The Environmental Damage Regulations 2015

The regulations oblige those who create environmental damage — whether by water pollution, adversely affecting protected species or sites of special scientific interest (SSSIs), or by land pollution that causes risks to human health — to not only cease the damage, but also to implement a wide variety of remedial measures to restore affected areas.

The Construction (Design and Management) Regulations (CDM) 2015

The regulations cover the management of health, safety and welfare when carrying out construction projects. CDM 2015 replaced the Construction (Design and Management) Regulations 2007. CDM 2015 aims to improve health and safety in the industry.

Flood and Water Management Act (FWMA) 2010

Pitt (2008) looked at lessons learned from the widespread flooding in 2007. Extensive recommendations were made, including recommendations to prevent new buildings in flood risk areas and to increase the resilience of existing buildings in floodplains. The report also brought essential services to the forefront, with several recommendations for Government and infrastructure operators to work together on increasing resilience of those assets. The Government's response to the Pitt review led to development of the Flood and Water Management Act 2010.

The Flood and Water Management Act aimed to provide better, more sustainable management of flood and coastal risks for people, homes, businesses, and the environment. EA will have powers to undertake sea flooding and coastal erosion works. Local authorities have powers to undertake coastal erosion works and sea flooding works with EA consent. The Regional Flood Defence Committees (RFDCs) have been replaced with the Regional Flood and Coastal Committees (RFCCs), which are the executive and advisory bodies.

For properties that are at flood risk, the 2010 Act does not require EA or local lead flood authorities to provide site-specific information that will enable site-specific resilience measures to be implemented, e.g. flood protection, flood warning. The design of coastal flood defences requires a design level and the consideration of hydrostatic pressure, wave loading and geotechnical conditions in accordance with relevant Eurocode and British Standards. BS 085500:2015 'Flood resistant and resilient construction' provides some guidance on mitigating the impact of flooding at individual property level.

The Flood Risk Regulations 2009

These regulations require the Assessment and Management of Flood Risk.

The Coast Protection Act 1949

This is one of the most important pieces of legislation about managing the coast. The Act provides the legal framework for the protection of the coast against erosion and encroachment by the sea within the boundaries set out in Schedule 4 of the Act. FWMA 2010 has made some changes to the Coast Protection Act 1949 (*EA, 2010*).

Floods Directive

The European Directive on the Assessment and Management of Flood Risks, known as the Floods Directive, came into force in November 2007. It requires Member States to assess whether watercourses and coastal waters are at risk from flooding, to map the flood extent and the assets and humans at risk in these areas, and to take adequate and coordinated measures to reduce this flood risk.

The Floods Directive will be implemented in coordination with the Water Framework Directive. The requirements of the Floods Directive are implemented in England and Wales through the Flood Risk Regulations 2009 and the Flood Risk (Cross Border Areas) Regulations 2010. These required the production of preliminary assessment maps and reports (by December 2011), the identification of significant flood risk areas, and for these areas, the development of flood hazard and flood risk maps (by December 2013) and flood risk management plans (by December 2015).

Water Resources Act 1991

The Act empowers EA in several areas:

- S165 (Sea defence): gives EA permissive powers to provide sea defences.
- S105 (Surveys & levies): EA retains the overall duty to carry out surveys of the areas in relation to which it carries out its flood defence functions and responsibility for the issuing of levies or the making of drainage charges.
- S165 (Outfalls): in the sea or estuaries EA may construct all such works and do all such things in the sea or in any estuary as may be necessary to secure an adequate outfall for a main river.
- S166 (Flood warning): EA has the power to provide and operate flood warning systems.

Land Drainage Act 1991

Gives powers to local authorities to carry out works on watercourses which are not designated as ‘main rivers’ and are not within the area of an Internal Drainage Board.

The Civil Contingencies Act

Requires Category 2 responders (utilities, telecoms) to have a business continuity plan in place. Furthermore, the Strategic Framework and Policy Statement (2010) outlines that the Critical Infrastructure Resilience Programme will seek to improve business continuity through best practice (BS 25999).

Environment Act 1995

The Act provided for the formation of the Environment Agency in England and Natural Resources Wales, and the Scottish Environment Protection Agency in Scotland.

Town and Country Planning Act 1990

Section 57 of this creates a general requirement that development of land should not be carried out except with planning permission. Section 55 defines 'development' as the carrying out of building, engineering, mining or other operations in, on, over or under land, or the making of any material change in the use of any buildings or other land.

The Food and Environment Protection Act (FEPA) 1985

The Act covers the issue of licences for dredging and the disposal of material at sea.

Harbours Act 1964

Harbours in general sit outside of the lengths of coast covered in the Coast Protection Act 1949. These areas are covered under the Harbours Act 1964.

National Planning Policy Framework (NPPF)

The development of buildings in flood risk areas is controlled by the National Planning Policy Framework (March 2012) in England, Planning Policy Wales, Scottish Planning Policy SPP7 and Planning Policy Statement PPS15 in Northern Ireland.

The National Planning Policy Framework sets out the Government's planning policies for England and how these are expected to be applied. The framework acts as guidance for local planning authorities and decision-makers, both in drawing up plans and making decisions about planning applications. The planning practice guidance to support the framework is published online and regularly updated (*Department for Communities and Local Government, 2012*). Within English policy for example, development is steered to low flood risk areas and development within higher flood risk areas requires site-specific flood risk assessments. Site-specific flood risk assessments are an appropriate tool to future proof the resilience of buildings. Hydraulic models considering sea levels, climate change, wave overtopping, local pathways, formal and designated defences are typically required to provide site-specific evidence. Some guidance on flood risk is provided in BS 8533:2017.

Local planning authorities should adopt proactive strategies to mitigate and adapt to climate change (Climate Change Act 2008) taking full account of flood risk, coastal change and water supply and demand considerations (Section 94, NPPF 2012). Local Plans should take account of climate change over the longer term, including factors such as flood risk, coastal change, water supply and changes to biodiversity and landscape. New development should be planned to avoid increased vulnerability to the range of impacts arising from climate change. When new development is brought forward in areas which are vulnerable, care should be taken to ensure that risks can be managed through suitable adaptation measures, including through the planning of green infrastructure (Section 99, NPPF 2012). Section 100 states that inappropriate development in areas at risk of flooding should be avoided by directing development away from areas at highest risk, but where development is necessary, making it safe without increasing flood risk elsewhere. Local Plans should be supported by Strategic Flood Risk Assessment and develop policies to manage flood risk from all sources, taking account of advice from EA and other relevant flood risk management bodies. Local Plans should apply a sequential, risk-based approach to the location of development to avoid where possible flood risk to people and property and manage any residual risk, taking account of the impacts of climate change, by applying the Sequential Test and if necessary, applying the Exception Test. Each of the tests are specific flood risk assessment methodology; detailed scopes of the tests are provided between Article 100 and 104 (NPPF, 2012). Please also see *Table 6* for the specific condition where Exception Tests are required for planning permission.

Guidance on flood risk and coastal change

Ministry of Housing, Communities & Local Government (2014) advises how to take account of and address the risks associated with flooding and coastal change in the planning process.

The developer must provide evidence to show that the proposed development would be safe and that any residual flood risk can be overcome to the satisfaction of the local planning authority, taking account of any advice from EA. The developer's site-specific flood risk assessment should demonstrate that the site will be safe and that people will not be exposed to hazardous flooding from any source. The following should be covered by the flood risk assessment:

- the design of any flood defence infrastructure;
- access and egress;
- operation and maintenance;
- design of development to manage and reduce flood risk wherever possible;
- resident awareness;
- flood warning and evacuation procedures;
- any funding arrangements necessary for implementing the measures.

Flood zones

Flood zones are geographic areas that have been defined according to varying levels of flood risk. These zones are depicted on a flood risk map published by EA. Each zone reflects the severity or type of flooding in the area. The definitions of the flood zones used by the Government are provided in *Table 4*.

Table 4. Definition of flood zones by the Environment Agency, England.

Flood zone	Definition
Zone 1 Low Probability	Land having a less than 1 in 1000 annual probability of river or sea flooding. (Shown as 'clear' on the flood map – all land outside Zones 2 and 3)
Zone 2 Medium Probability	Land having between a 1 in 100 and 1 in 1000 annual probability of river flooding; or land having between a 1 in 200 and 1 in 1000 annual probability of sea flooding. (Land shown in light blue on the flood map)
Zone 3a High Probability	Land having a 1 in 100 or greater annual probability of river flooding; or land having a 1 in 200 or greater annual probability of sea flooding. (Land shown in dark blue on the flood map)
Zone 3b The Functional Floodplain	This zone comprises land where water has to flow or be stored in times of flood. Local planning authorities should identify in their Strategic Flood Risk Assessments areas of functional floodplain and its boundaries accordingly, in agreement with EA. (Not separately distinguished from Zone 3a on the flood map)

Note: these flood zones refer to the probability of rivers and sea flooding, ignoring the presence of defences.

Flood risk vulnerability classification

The flood risk vulnerability classification defined in NPPF is shown in *Table 5*.

Table 5. Flood risk vulnerability classification based partly on Department for Environment, Food and Rural Affairs and Environment Agency research on Flood Risks to People (FD2321/TR2) and also on the need of some uses to keep functioning during flooding.

Essential infrastructure
- Essential transport infrastructure (including mass evacuation routes) which has to cross the area at risk
- Essential utility infrastructure which has to be located in a flood risk area for operational reasons, including electricity generating power stations and grid and primary substations; and water treatment works that need to remain operational in times of flood
- Wind turbines

Highly vulnerable
- Police stations, ambulance stations and fire stations and command centres and telecommunications installations required to be operational during flooding
- Emergency dispersal points
- Basement dwellings
- Caravans, mobile homes and park homes intended for permanent residential use
- Installations requiring hazardous substances consent. (Where there is a demonstrable need to locate such installations for bulk storage of materials with port or other similar facilities, or such installations with energy infrastructure or carbon capture and storage installations, that require coastal or water-side locations, or need to be located in other high flood risk areas, in these instances the facilities should be classified as 'essential infrastructure')

More vulnerable
- Hospitals
- Residential institutions such as residential care homes, children's homes, social services homes, prisons and hostels
- Buildings used for dwelling houses, student halls of residence, drinking establishments, nightclubs and hotels
- Non-residential uses for health services, nurseries and educational establishments
- Landfill and sites used for waste management facilities for hazardous waste
- Sites used for holiday or short-let caravans and camping, subject to a specific warning and evacuation plan

Less vulnerable
- Police, ambulance and fire stations which are not required to be operational during flooding
- Buildings used for shops, financial, professional and other services, restaurants and cafés, hot food takeaways, offices, general industry storage and distribution, non-residential institutions not included in 'more vulnerable', and assembly and leisure
- Land and buildings used for agriculture and forestry
- Waste treatment (except landfill and hazardous waste facilities)
- Minerals working and processing (except for sand and gravel working)
- Water treatment works which do not need to remain operational during times of flood
- Sewage treatment works (if adequate measures to control pollution and manage sewage during flooding events are in place)

Water-compatible development
- Flood control infrastructure
- Water transmission infrastructure and pumping stations
- Sewage transmission infrastructure and pumping stations
- Sand and gravel working
- Docks, marinas and wharves
- Navigation facilities
- Ministry of Defence defence installations
- Ship building, repairing and dismantling, dockside fish processing and refrigeration and compatible activities requiring a waterside location
- Water-based recreation (excluding sleeping accommodation)
- Lifeguard and coastguard stations
- Amenity open space, nature conservation and biodiversity, outdoor sports and recreation and essential facilities such as changing rooms
- Essential ancillary sleeping or residential accommodation for staff required by uses in this category, subject to a specific warning and evacuation plan

Notes:

a. This classification is based partly on Department for Environment, Food and Rural Affairs and Environment Agency research on Flood Risks to People (Defra, 2006) and also on the need of some uses to keep functioning during flooding.

b. Buildings that combine a mixture of uses should be placed into the higher of the relevant classes of flood risk sensitivity. Developments that allow uses to be distributed over the site may fall within several classes of flood risk sensitivity.

c. The impact of a flood on the particular uses identified within this flood risk vulnerability classification will vary within each vulnerability class. Therefore, the flood risk management infrastructure and other risk mitigation measures needed to ensure the development is safe may differ between uses within a particular vulnerability classification.

Flood risk vulnerability and flood zone 'compatibility'

NPPF clearly defines what types of development are permitted in each flood zone as summarised in *Table 6*.

Table 6. NPPF-defined flood risk vulnerability and flood zone 'compatibility'.

Flood zones	Flood risk vulnerability classification				
	Essential infrastructure	Highly vulnerable	More vulnerable	Less vulnerable	Water compatible
Zone 1	✓	✓	✓	✓	✓
Zone 2	✓	Exception test required	✓	✓	✓
Zone 3a	Exception test required	x	Exception test required	✓	✓
Zone 3b	Exception test required	x	x	x	✓

Key:
✓ Development is appropriate.
x Development should not be permitted.

In the UK, coastal flooding is considered to be the second highest risk for causing civil emergency (*Cabinet Office, 2017*). It is therefore important to prioritise and identify early signs of future threats and trends to ensure solutions for managing coastal flood risk during this century and beyond.

Adaptation pathways to manage growing coastal flooding due to climate change is one of the key emerging issues. The adaptive pathways approach for managing flooding risk, introduced in the Thames Estuary 2100 project for London, has gained recognition and could be applied much more widely (*Nicholls et al., 2015*).

Implementation of managed realignment (or managed retreat) as a *soft engineering* solution for flood defence and inter-tidal habitat creation (*Cooper, 2003*) is also getting recognition, e.g. Medmerry in Sussex and Steart Marshes in Somerset.

Temporal clustering of extreme events (*Dissanayake et al., 2015*; *Haigh et al., 2016*) was especially noteworthy during the 2013/14 and 2015/16 winter events, which caused large-scale flooding. Ten of the leading universities in the UK undertook a joint research project 'Flood MEMORY' to better understand the clustered statistics of flooding events (*Haynes et al., 2016*). Multi events have important implications for financial and practical aspects of risk management (in areas such as re-insurance, infrastructure reliability and emergency response).

Another emerging issue relates to changes in tidal range, which could affect coastal flooding in the future. It has generally been considered that tides have undergone little change over the last century, and it is often presumed that they will not change significantly over the next century. However, several studies have detected measurable changes in tides during the 20th century and the early part of the 21st century at several locations (see *Mawdsley et al., 2015*, for a review) and modelling studies have predicted changes in tidal range around the UK, with future changes in mean sea level (*Pickering et al., 2012*; *Pelling et al., 2013*).

Sea level rise is very closely linked to increasing global temperatures. The Intergovernmental Panel on Climate Change (IPCC) in its Fourth (2007) and Fifth (2013) Assessment Reports has made projections of future changes in mean sea level, storm surge and wave climate due to climate change globally. The UK has moved from using UK Climate Projections (UKCP) 2002 (UKCP02) to UKCP09 and is now looking ahead to UKCP18. The UKCP18 project will update the UKCP09 projections over UK land areas and update projections of sea level rise, giving greater regional detail. Projections of mean sea level rise have varied by a few tens of cm in these assessments, but there is consensus that mean sea level will continue to rise and at an accelerated rate due to climate change.

- Sea level rise by 2100 may well exceed 1 m; it could easily reach 1.5 m and a rise of up to 2 m could not be ruled out.
- There is no clear evidence on increases in the total number of storms, but intensities may increase.

Even as uncertainties remain about how much the sea level may rise this century, it is certain that sea level rise in this century and beyond will pose a growing challenge to coastal communities, infrastructure and ecosystems from increased (permanent) inundation, more frequent and extreme coastal flooding, and coastal erosion. Assessment of vulnerability of infrastructure to rising sea levels requires consideration of historical evidence and projections in the future. It is also very important to understand how changing sea level and tidal range alter the coastal zone and interact with coastal flood risk at local scales.

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Bathymetry
Depth of water in estuaries, coasts, oceans, seas and lakes; generally surveyed with reference to chart datum.

Coastal morphodynamics
Refers to the interaction and adjustment of the seafloor topography and fluid hydrodynamic processes, seafloor morphologies and motion of sediment. Hydrodynamic processes include those of waves, tides, and wind-induced currents.

Harmonic tidal constituents
Empirical coefficients used to predict tide levels which correspond to harmonic elements in a mathematical expression of the tide-producing force, and in corresponding formulae for the tide or tidal stream. Each constituent represents a periodic change of relative position of the Earth, Sun and Moon; e.g. Major Tidal Constituents Lunar (M2, L2 and N2 etc.) and Major Tidal Constituents Solar (S2, T2 and K2 etc.).

Ordnance datum
The mean sea level as defined for Ordnance Survey; mean sea level calculated from observation taken at Newlyn, Cornwall, and used as the official basis for height calculation on British maps.

Soft engineering
Long-term, more sustainable engineering with less impact on environment; e.g. managed retreat or managed re-alignment of coastal protection.

Wave overtopping
A condition where a wave overtops a defence towards landward direction.

Abbreviations

AEP	Annual exceedance probability
AIMS	Asset Information Management System
BODC	British Oceanographic Data Centre
CCIP	Climate Challenge Integration Plugfest
CDM	Construction Design and Management
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CFB	Coastal Flood Boundary dataset
CS3X	12 km shelf model for storm surge prediction
Defra	Department for Environment, Food and Rural Affairs
DTM	Digital Terrain Model
EA	Environment Agency
EMODnet	European Marine Observation and Data Network
FEPA	The Food and Environment Protection Act 1985
FFC	Flood Forecasting Centre
FFFS	Future Flood Forecasting System
FFW&R	Flood Forecasting Warning and Response
FRM	Flood Risk Management
FWMA	Flood and Water Management Act 2010
IPCC	Intergovernmental Panel on Climate Change
JPC	Joint Probability Contours
NCEP	National Centers for Environmental Prediction
NEMO	Nucleus for European Modelling of the Ocean
NEXTMap	Database for worldwide elevation data
NFFS	National Flood Forecasting System
NOC	National Oceanography Centre
NPPF	National Planning Policy Framework
NTSLF	National Tidal and Sea Level Facility
OGL	Open Government Licence
PLA	Port of London Authority
RFCCs	Regional Flood and Coastal Committees
RFDCs	Regional Flood Defence Committees
SEPA	Scottish Environment Protection Agency
SFDAD	Scottish Flood Defence Asset Database
SFRM	Strategic Flood Risk Management
SoN	State of the Nation
S-P-R-C	Source-Pathways-Response and Consequence model

SRTM	Shuttle Radar Topography Mission
UKCFF	United Kingdom Coastal Flood Forecasting
UKCMF	United Kingdom Coastal Monitoring and Forecasting Services
UKCP	United Kingdom Climate Projections
UKCP09	United Kingdom Climate Projections 2009
UKCP18	United Kingdom Climate Projections 2018
UKHO	United Kingdom Hydrographic Office
UKTGN	United Kingdom Tide Gauge Network

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