Climate change impacts on coastal flooding relevant to the UK and Ireland

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KEY FACTS

What is happening

- Extreme water levels have become more frequent in the past 150 years, driven primarily by mean sea level rise.
- Mean sea-level rise and coastal squeeze (and changes in sediment supply) are contributing to a decline in the extent of saltmarshes, shingle beaches and sand dunes, which act as a natural buffer to flooding.
- Exposure to flooding is being exacerbated by population growth, changes in land use and increasing asset values in floodplains.
- Increased flood risk has largely been contained through improved flood defences, flood forecasting and emergency response. However, losses in major events that exceed defence design standards are growing.

What could happen

- Extreme water levels are certain to increase during the 21st century and beyond, principally driven by accelerating mean sea-level rise.
- Continued loss of natural habitat buffers will dramatically increase defence capital and maintenance costs.
- By the 2080s, at current adaptation levels, estimated annual coastal flood damages is likely to increase two- to three-fold from £360 million today, depending on temperature rise and population growth.

Citation: Haigh, I.D., Dornbusch, U., Brown, J., Lyddon, C., Nicholls, R.J., Penning-Roswell, E. and Sayers, P. Climate change impacts on coastal flooding relevant to the UK and Ireland. *MCCIP Science Review 2022*, 18pp.

doi: 10.14465/2022.reu02.cfl

Submitted: 07 2022
Published online: 11 2022

- 1,600 km of major roads, 650 km of railway, 92 railway stations and 55 historical landfill sites are likely to be at risk of coastal flooding or erosion by the end of the century.
- Socially vulnerable communities at the coast are disproportionally at risk, and this will increase more rapidly than for other communities, widening inequalities.

SUPPORTING EVIDENCE

Introduction

Coastal floods are amongst the most dangerous natural hazards globally. This also applies to the UK, where flooding is one of the highest priority risks for civil emergencies (Cabinet Office, 2015). Recent floods (e.g., over the winter of 2013/14 and 2019/20) have demonstrated the ever-present threat of serious flood impacts in coastal regions, despite improved flood-protection measures and technology that has provided tools to forecast and mitigate risks. While flood-defence standards in the UK are among the highest in the world, significant populations and assets in the coastal flood plain are threatened in the event of defence failure during events exceeding the standard of protection (e.g., major overtopping or a breach). The third Climate Change Risk Assessment estimates that the present-day expected annual economic damages from coastal flooding in the UK are around £360 million (Sayers *et al*., 2020). Furthermore, coastal flooding is a growing threat due to accelerating mean sea-level rise and possible changes in tides and storminess associated with climate change (Palmer *et al*., 2018; Fox-Kemper *et al*., 2021), as well as continued decline in the extent of natural habitats like saltmarshes, shingle beaches and sand dunes. Impacts of coastal flooding could also continue to increase in the future as flood defences age and with population growth, urbanisation and continued development in low-lying coastal areas (Stevens *et al*., 2016).

Throughout history, many severe flooding events have affected the UK coast (Haigh *et al*., 2015; 2017). In 1607, a major coastal flood on the west coast caused the deaths of around 2000 people (Horsburgh and Horritt, 2006). The 'Big Flood' of 31 January–1 February 1953, killed up to 300 people in eastern England and 30 people in Scotland, and damage costs were £1.2 billion, at 2014 values (McRobie *et al*., 2005). During 2013/14, the UK experienced an unusual sequence of storms and some of the most significant coastal floods in the last 60 years (Spencer *et al*., 2015).

The multiple drivers of coastal flood risk can be considered using the conceptual Source−Pathway−Receptor−Consequence (SPRC) model (Figure 1; Sayers *et al*., 2002). The 'source' describes the origin of a hazard, which in the case of coastal floods, is extreme total water levels (Moritz *et al*., 2017). The 'pathway' is the route that a hazard takes to reach the 'receptors', the processes mediating the magnitude of the hazard along that route and the characteristics of the coastline that influence the hazard. For coastal flooding it reflects how seawater makes its way onto normally dry land. The 'receptor' is the entity (e.g., people, property, environment) that may be harmed by the hazard (e.g., seawater inundation and/or wave impact). 'Consequences' entail the social, economic and environmental effects of the coastal flooding on the receptors, the calculation of which are extremely sensitive to small changes in the source conditions (Lyddon *et al*., 2020).

This MCCIP report card is based on the SPRC framework and updates the previous report cards on coastal flooding (Donovan *et al*., 2013; Haigh and Nicholls, 2017; Haigh *et al*., 2020a). We describe what is already happening and what could happen in the future using the SPRC components; we show how change can increase flood risk, and how coastal management can reduce flood risk. We then state what qualitative level of confidence we can place in the science for 'what is already happening' and 'what could happen in the future'. Finally, we briefly highlight key challenges and emerging issues.

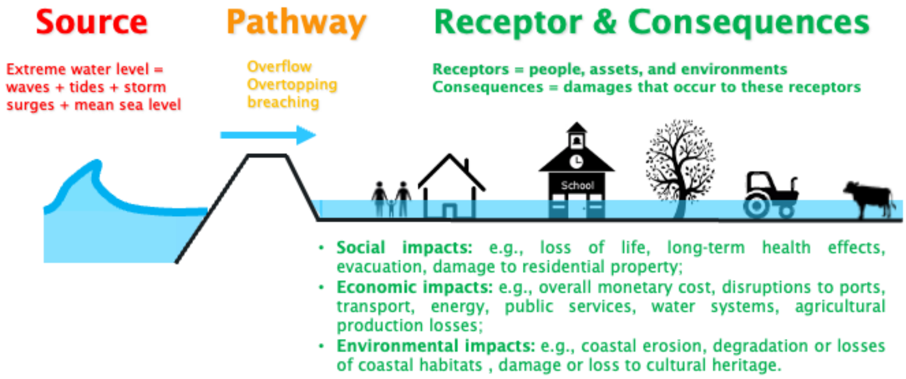


Figure 1: Source-Pathway-Receptor-Consequence (SPRC) conceptual model. (Adapted from Sayers et al, 2002.)

WHAT IS ALREADY HAPPENING?

Source

Coastal floods are driven by extreme total water levels, which arise as combinations of: (1) relative mean sea level; (2) astronomical tides; (3) storm surges; and (4) waves, especially setup and runup. These factors experience topographic amplification near the coast and there are non-linear interactions between the four components. The additional influence of rainfall and fluvial input may also be significant in some estuaries dependent on size, river regime and transmission time (Svensson and Jones, 2002; Hendry *et al*., 2019; Robins and Lewis, 2019; Harrison *et al*., 2021). These four components exhibit considerable natural seasonal and year-to-year variability. Although the tidal component is deterministic, with predictable modulations on fortnightly, monthly, seasonal, 4.4-year and 18.6-year timescales (Haigh *et al*., 2011), the variability in the wave, storm surge and mean sea-level components is stochastic and linked to regional climate cycles, such as the North Atlantic Oscillation (Hurrell, 1995). The seasonal and year-to-year variability in each component influences the potential frequency and magnitude of flooding (Wadey *et al*., 2014). Longer-term changes in any, or all, of the components can lead to variations in the frequency and magnitude of extreme sea levels. For the North Sea, Horsburgh *et al*. (2021) assessed 'grey swan' extreme water-level events (i.e., an event which is expected on the grounds of natural variability but is not within the observational record). They suggest that over the next few decades, the natural variability of mid-latitude storm systems is likely to be a more-important driver of coastal extreme sea levels around the UK coast than either mean sea-level rise or climatically induced changes to storminess.

Extreme water levels are affected by changes in relative mean sea level both directly and indirectly. With mean sea-level rise, a lower storm surge elevation at high tide is necessary to produce directly a sea level high enough to cause flooding. Changes in mean sea level alter water depths and therefore indirectly modify the propagation and dissipation of the tide and storm surge components (Lyddon *et al*., 2018a), or alter wave processes in shallow water (e.g. refraction; Dornbusch, 2017), without any change in the frequency of occurrence of extreme events. In addition, extreme water levels may change with variations in the speed, tracks and strengths of weather systems, which alter the frequency, intensity and/or duration of storm surges and waves (Palmer *et al*., 2018; Wei *et al*., 2019) and variations in rainfall and river discharge in estuaries (Robins *et al*., 2021). Finally, the relative importance and duration of influence of any of the four sea-level components, and fluvial input, is linked to the local tidal range and wave exposure, with some (e.g., mean sea-level rise) having higher impacts in low-energy micro- than in high-energy macro-tidal environments.

Current trends in still-water levels (the level that the sea surface would assume in the absence of wind waves), and storms and waves, are detailed in report cards by Horsburgh *et al*. (2020) and Wolf *et al*. (2020), respectively. In brief, there is overwhelming scientific consensus that observed increases in extreme still-water levels around the UK and worldwide have been driven primarily by the rise in relative mean sea level (as illustrated for Newlyn in Cornwall, UK, Figure 2). As a result, extreme sea levels that previously had a long return period (>100 years) near the beginning of the 20th century now have much lower (~10 year) return periods. There is little evidence for long-term systematic changes in storminess or storm surge magnitude over the last 100 years above natural variability (Marcos *et al*., 2015; Mawdsley and Haigh, 2016), although a recent paper challenges this view (Calafat *et al*., 2022). There is some observational evidence for small changes in tidal range at select sites around the UK and elsewhere worldwide (Haigh *et al*., 2020b). Such changes to tides could therefore impact extreme water levels and their associated probability of occurrence. Over the last 100 years changes in tides have been shown to slightly increased or decreased extreme high-water levels around the UK coast (Mawdsley *et al*., 2015). The drivers of these changes remain unclear, although it is likely that they relate to changes in local bathymetry (mainly dredging for navigation) and/or climate-related variations (Haigh *et al*., 2020b). It has proved difficult to accurately assess current and historical changes in the wave climate due to the lack of long-term wave measurements and because trends are obscured by large natural variability (Wolf *et al*., 2020). However, positive regional trends in extreme wave heights have been reported at several locations in the North-East Atlantic since the late 1970s (Wolf *et al*., 2020).

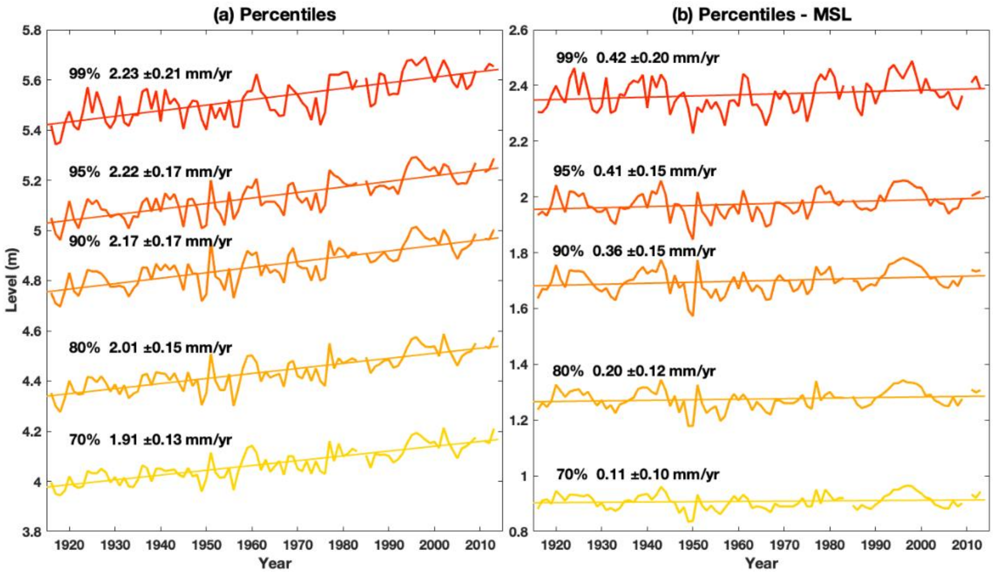


Figure 2: Trends in high-water level percentiles at Newlyn, Cornwall, UK (a) before; and (b) after, removing the influence of relative mean sea-level (MSL) rise. The magnitude of the trend is given in mm/yr with a standard error. Trends in the different high-water level time-series measurements are all statistically significant at 95% confidence (i.e., two standard errors), but after removing the mean sea level none of the trends is statistically significant.

Pathway

The nature of flood pathways varies around the coast and is primarily determined by natural features and their topography or engineered hard defences. Seawater can inundate normally dry land via several different pathways. First, by still water simply overflowing where the water height exceeds the elevation of the land or the barrier that normally separates them. Second, by overtopping of a natural (e.g., barrier beaches) or artificial (e.g. sea wall) barrier by waves (Brown *et al*., 2021). Third, by breaching and lowering of a natural or artificial barrier, often as a consequence of prolonged overwashing or erosion at the front-face of the barrier allowing more water to flow landward. Decline in natural features, and deterioration in artificial human made ones over time (e.g., due to lack of funding), impact flood pathways and can increase flood hazard. In contrast, for example, artificial nourishment and stabilisation of beaches, replacement of beaches with hard defence (Dornbusch, 2019), building new or maintaining and improving existing banks along estuaries, or providing more space for water through managed re-alignment can alter flood pathways and reduce flood risk (Huguet *et al*., 2018). Management interventions can increase flood risk if not appropriate for the site, and numerical modelling tools can be used to consider the site-specific impacts of new, artificial or human-made features (Pontee, 2015). Larger scale changes in subtidal morphology like dredging (van Maren *et al* 2015; Ralston *et al*., 2018) can influence both the source (tidal range) and also flood pathways (changes in sediment regime) (Philips *et al*., 2017).

Determining historical trends in flood Pathways is more difficult than in the Sources component, due to the combined natural and human elements at play and the lack of appropriate long-term datasets (e.g., saltmarsh extents, full history of flood defences, etc.). However, innovative approaches are starting to be developed to assess changes in flood pathways for more-recent time periods, using, for example, social media (e.g., Brown *et al*., 2021) and novel measurement technologies (e.g., WireWall, which measures the speed and volume of overtopping; Figure 3). It is increasingly recognised that natural systems, such as saltmarshes, shingle beaches and sand dunes, provide important buffering against floods and are in decline, which has increased flood risk (Committee on Climate Change, 2018). These natural systems are only part of the pathway and influence them by reducing wave height in some locations in front of human-made defences, or reducing the water volume in case of a breach by maintaining a higher sill level in the breach area.

Figure 3: A hard-engineered coastline with railway infrastructure and a new wave overtopping measurement system, 'WireWall'. Photo from the University of Plymouth's Dawlish camera installed as part of the Coastal REsistance: Alerts and Monitoring Technologies (CreamT) project.

Current flood risk would be far higher without the decades of investment into extensive flood risk management infrastructure (Environment Agency, 2014). While hard defences to hold the line require increasing investment in maintenance and lock society into the cycle of failure and rebuilding, nature-based defences are more sustainably but require space to evolve. Data on flood defences over time is not well developed. Massive investments in defences have occurred over the 20th and early 21st century. Events such as the 1953 flood were an important trigger. It is estimated that about 720,000 properties were protected from the high sea levels during the 5–6 December 2013 event because of flood defences (Environment Agency, 2016). However, flood defences were damaged during the 2013/14 season and the cost of repair (including fluvial defences) has been estimated to be approximately £147 million (Environment Agency, 2020), thus more-proactive planning is now apparent. Nearly a quarter of England's coast is now defended (Sayers *et al*., 2015) and several new schemes are being built or are planned, such as those associated with Thames Estuary 2100 (Environment Agency, 2012). The UK also has movable storm surge barriers, including the Thames Barrier, and smaller barriers in the Thames, Hull, Ipswich and Boston. The Thames and Hull barriers close on average 2 and 12 times per year, respectively. The Thames Barrier was closed an 'exceptional' 50 times in the winter of 2013/14, the maximum recommended number, but this was predominantly to manage high fluvial flows highlighting the fluvial/coastal relationship of the source in estuaries.

Receptors and Consequences

Receptors and consequences are linked, and so we deal with them together here. For past coastal flood events, Haigh *et al*. (2017) record 15 types of consequences, broadly grouped into social (e.g., loss of life, number of people evacuated, damage to residential property), economic (e.g., overall monetary cost, disruptions to ports, transport, energy, public services, water systems, agricultural production losses) and environmental (e.g., coastal erosion, degradation or losses of coastal habitats, damage, or loss to cultural heritage) impacts. The consequences of a flood can be long-lasting (e.g., injury or long-term physical and mental health effects; Jackson and Devadason, 2019). For example, it is thought that anxiety and disruption of the evacuation and loss of belongings during the 26 February 1990 coastal floods in Towyn in Wales contributed to the premature death of about 50 people (Wales Audit Office, 2009). The consequences of a flood can also extend outside of the area of coastline directly impacted, because of, for example, disruption to transport or supply chains (Dawson *et al*., 2016).

As rising mean sea levels increase flood risk, so does the growth in the number of receptors in flood-prone areas. Stevens *et al*. (2016) assessed changes in the incidents of flooding across the UK, from all sources (including fluvial) and found that the increase in the total number of reported flood events in the 20th century is dominantly controlled by growth in the number of receptors. From 2005 to 2014, the National Trust (2015) found this trend continued in coastal areas, with 15,000 new buildings built in areas subject to flooding and erosion. Changes in land use and increasing asset values in floodplain areas have also enhanced exposure to coastal flooding. Despite this growing loss potential, evidence from Haigh *et al*. (2017) suggests that the number and consequences of coastal floods appear to have declined since 1915 in the UK, reflecting better defences and improvements in flood forecasting, warning, emergency response and planning. Wider efforts at improved adaptation should also be noted, particularly in recent decades, which has resulted in a reduction in flood risk. Spatial planning and building codes are already very effective at reducing the risk to new build properties in coastal flood plains (Sayers *et al*., 2015). For example, new properties in the coastal flood plain are generally raised above flood levels, including an allowance for mean sea-level rise. However, adaptation options like Coastal Change Management Areas have had, 10 years after their introduction, limited take-up (Kirby *et al*., 2021).

WHAT COULD HAPPEN IN THE FUTURE?

Source

Future trends in still-water levels, and storms and waves for the UK are detailed in companion report cards (Horsburgh *et al*., 2020; Wolf *et al*. 2020). These draw significantly on the UKCP18 projections (Palmer *et al*., 2018). There is high confidence that the regional mean sea level will continue to rise around the UK, and the likely range (90% confidence) is between 0.27 and 1.12 m by 2100 (excluding vertical land motions). There is low confidence in regional projections of storminess and associated changes in storm surges and waves. Recent regional and global sea level projections are available from the latest Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6; Fox-Kemper *et al*., 2021); Considering only processes for which projections can be made with at least medium confidence, relative to the period 1995–2014, global mean sea level estimated by AR6 by 2100 are between 0.38 [0.28–0.55, likely range] m (SSP1-1.9) and 0.77 [0.63–1.02] m (SSP5-8.5). This rise is primarily caused by thermal expansion and mass loss from glaciers and ice sheets, with minor contributions from changes in land-water storage and does not include those ice-sheet-related processes that are characterised by deep uncertainty. Larger rises are considered possible (up to 2.3 m by 2100), due to a range of possible processes including marine ice sheet instabilities (MISI) or marine ice-cliff instabilities (MICI) (Fox-Kemper *et al*., 2021), but assessing their likelihood is difficult. Recently van de Wal *et al*. (2022) presented physically plausible high-end mean sea level scenarios using an approach complementary to the IPCC AR6 report.

Reducing human emissions of greenhouse gases will stabilise the temperature in about a century but mean sea-level rise will continue for many centuries even if the temperature is stabilised, because it takes many hundreds of years for the cryosphere and the deepest parts of the ocean to adjust to increased air temperatures. The UK coast will be subject to at least 1 m of mean sea-level rise, it is just a matter of when (Committee on Climate Change, 2018).

Several modelling studies have predicted regional changes in tidal range resulting from future changes in mean sea level (Haigh *et al*., 2020b). These studies suggest that changes in tidal range will typically be in the order of plus or minus 10% of any changes in mean sea level, which could slightly enhance or lessen coastal flooding at some locations. Extreme water levels are therefore very likely to increase during the 21st century, driven primarily by the changes in relative mean sea level, rather than any changes in storminess, with some modifications at select sites due to changes in the magnitude and timing of tides. Future coastal flooding could also vary because of changes in sediment pathways and morphology (especially in estuaries; Lyddon *et al*., 2018b), which may result from mean sea-level rise, variations in the wave climate, or anthropogenic processes (e.g. dredging).

Pathway

With mean sea-level rise and coastal squeeze (and any future changes in sediment supply), there is likely to be a continued decline in the extent of saltmarshes, shingle beaches and sand dunes over the coming century and beyond. This will lead to defence capital and maintenance costs increasing dramatically, as natural buffering effects are reduced. Changes in flood pathways will be closely linked to future policy decisions. Strategic shoreline management planning has been implemented since the 1990s in England and Wales, and it currently selects one of four options over three-time epochs going to 100 years in the future where: (1) Managed Realignment (including Adaptive Management) covers the option space between ;(2) Hold the Line; and (3) No Active Intervention; and with (4) Advance the existing defence line very rarely implemented (Hosking, 2006). The Committee on Climate Change (2018) calculated that implementing the current Shoreline Management Plans would cost £18−30 billion for England, depending on the rate of climate change. Maintaining the 1,460 km of coastline designated as ‘hold the line’ to the end of the century, achieves a lower benefit-cost ratio than the flood and coastal erosion risk management interventions that the government fund today. Therefore, on this basis, funding to protect some of these coastal stretches is unlikely. In addition, more-detailed Coastal Defence Strategies subdivide the hold the line approach into one that maintains the present defence crest height (accepting a decline in the standard of defence with climate change) and one that sustains the standard of defence. The increasing lengths of coastline where it is only justified to maintain crest heights, thus automatically leads to a gradual increase in flood risk.

Sayers *et al*. (2015) assessed the relationship between mean sea-level rise and the length of existing coastal defences that will become very difficult to maintain as mean sea-levels rise (Figure 4). The analysis suggests that the length of coastal defences ‘highly vulnerable’ to failure would almost double under 0.5 m mean sea-level rise, with the number of properties affected if these were lost rising by around 160%. Under a more-extreme scenario (2.5 m of global mean sea-level rise), the length of highly vulnerable defences is projected to triple and the number of properties affected by flooding if these defences where lost would increase by 490%. Many shingle beaches cannot be maintained under future mean sea-level rise, primarily because they cannot naturally adapt by rolling back (Dornbusch, 2017), leading to an acceleration of replacing them with hard structures (Dornbusch, 2019) with impacts on the natural environment and amenity they support. If the Thames Barrier continues to be used for managing both river flow and tidal flood events, future sea-level rise is predicted to make the number of closures unsustainable by around 2034; if used only for tidal flooding, this lifespan is predicted to extend to around 2070 (Environment Agency, 2016). The Thames Estuary 2100 plan (Environment Agency, 2012) includes options for a new Thames Barrier, which would be built farther downstream of the current one.

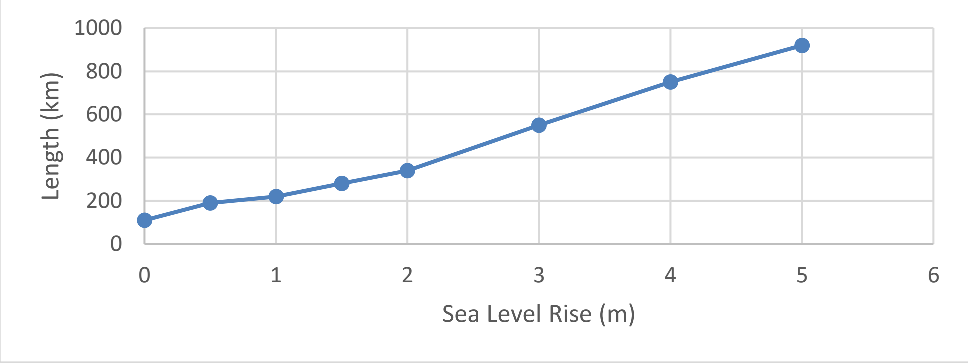


Figure 4: The length of coastal flood defences that may become highly vulnerable as mean sea-levels rise (source: Sayers et al., 2015).

Receptors and Consequences

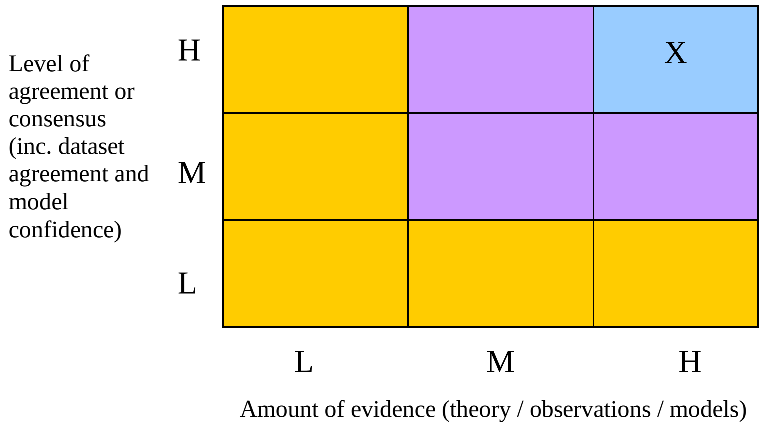
Population growth and accompanying development are likely to continue, particularly in areas that are currently defended and have a 'hold the line' management policy (Sayers *et al*., 2015). Therefore, significant and growing populations and assets will remain located in the coastal flood plain and will be at increasing risk in the event of a defence failure. Furthermore, compared to the national average, more socially vulnerable communities at the coast are disproportionally at risk and will see their risk increase more rapidly with climate change than elsewhere (Sayers *et al*., 2017). Significant investment in existing and new flood defence schemes are likely to continue, for heavily populated and developed regions, but are unlikely for sparsely populated ones (Committee on Climate Change, 2018). Land-use planning decisions and insurance policies will play a large role in determining future trends. Avoiding inappropriate development in the floodplain will reduce future exposure to flood risk and decrease the consequences when they occur. If insurance policies are changed such that flooded properties are restored, but in more flood-resilient ways with property-level protection or in areas of less risk, this could reduce flood consequences over time.

Mean sea-level rise is a relatively gradual change, and thus provides the time and opportunity for rethinking coastal communities into ones that are adapted to live with water (Building Futures, 2010) by having, for example, houses on stilts or floating houses in areas of low wave-exposure and moving communities out of flood risk areas where wave exposure is higher or additional risk factors are also increasing (Buser, 2020). Continued improvements to the flood forecasting (particularly in regard to forecasting impacts) and warning service will allow evacuations and/or preventative measures to be appropriately installed prior to events, such as temporary flood barriers or pumping stations that reduce consequences of flooding.

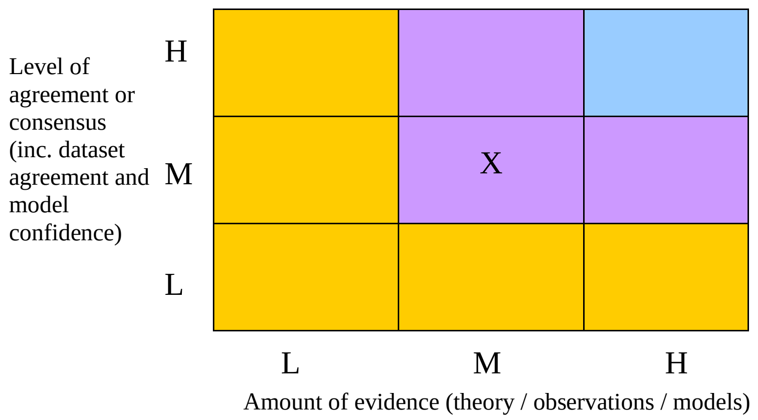
Projections of potential future coastal flooding impacts to the 2080s have been made by Sayers *et al*. (2015, 2020) and are usefully summarised together with other coastal risk literature in Edwards (2017). The latest analysis presented in third UK Climate Change Risk Assessment (CCRA; Sayers *et al*. 2020) is based on two climate-change scenarios (2^{o}C and a 4^{o}C rise in global mean surface temperature by 2100), two population growth projections (low and high), and three adaption scenarios (including the current and assumed enhanced and reduced adaptation levels when compared to present day). The analyses concluded that expected annual damages are estimated to more than double from £360 million today to £0.64−1.0 billion by the 2080s in the 2°C/low population and 4°C/high population future given a continuation of current levels of adaptation. The analysis suggests there are 544,000 residential properties and 72,000 non-residential properties within England's coastal floodplain today alone. After taking into account existing coastal defences (including both their condition and standard of protection) around ∼47,000 residential properties and ∼11,000 non-residential properties remain exposed to flooding more frequently than 1in75 years on average. The analysis goes on to consider how these risks may change given a combination of climate change and adaptation assumptions. Assuming a 2°C rise in GMST by the end of the century (compared to pre-industrial times), low population growth and limited adaptation (with present day protection standards reducing in all but major urban conurbations) the number of residential properties exposed to a significant chance of flooding increases six-fold to ∼290,000 by the 2080s. Assuming a 4°C rise in GMST, coastal risk is projected to increase tenfold to ∼470,000 by the 2080s given the same limited adaptation effort and high population growth. The Committee on Climate Change (2018) estimate approximately 1,600 km of major roads, 650 km of railway, 92 railway stations and 55 historical landfill sites are likely to be at risk of coastal flooding or erosion by the end of the century. The critical Dawlish line is projected to suffer serious reliability issues due to flooding by 2040, with line restrictions increasing from 10 days per year to 30–40, and maintenance costs tripling or quadrupling (Dawson *et al*. 2016). Sayers *et al*. (2022) explored the scale of transformational challenge in responding to changing coastal flood risks through to 2100 in England, considering relative mean sea-level rise and the local lowering of the foreshore platforms due to increased wave-driven surface erosion. Their results suggest ~30% (1,600-1,900 km) of England's shoreline currently designated as a 'Hold-the-Line' policy is likely to see increasing pressures to realign, assuming a rise in global mean surface temperatures of between 2 and 4°C by 2100. This has implications for ∼120,000–160,000 residential and non-residential properties by the 2050s; although it is not possible to say how many of these properties will require relocation (as this will be a matter for local and national choices) a proportion will.

CONFIDENCE ASSESSMENT

What is already happening?



What could happen in the future?



Confidence in what is already happening with coastal flooding has increased from ‘low’ to ‘high’, over the lifespan of the MCCIP report cards. It remains ‘high’ here as there is a high level of consensus that: (1) extreme water levels are increasing in frequency due to rising mean sea levels, (2) that to date we managed this sufficiently to contain growth in flood risk, and (3) nonetheless losses in a major event – above defence design standards − are growing. Confidence in what could happened in the future remains the same as previous, ‘medium’. While it is very likely extreme water levels and wave overtopping events will increase in frequency with mean sea-level rise, possible changes in the wave- and storm surge-climate and their spatially varying contribution to flood hazard, beyond natural variability, remain uncertain and there is considerable uncertainty in how flood pathways and receptors will change in the future (Environment Agency, 2020).

KEY CHALLENGES AND EMERGING ISSUES

Top challenges:

1. Given that mean sea levels will continue to rise for many hundreds of years, we need to rethink how coastal communities can adapt to live with water. We need to consider how long-term aspiration can be realised in the planning system to deliver practical portfolios of adaptation options that are technically feasible, balance costs and benefits, can attract appropriate finance, are socially acceptable and can be prepared for and implemented before the need for adaptation becomes urgent. We need to continue to move away from a coastal defence mindset (defence has a clear military connotation and it reflects our thinking that we are in a constant battle to protect coastal communities from the sea) to coastal management, where we consider a wider range of options in a more flexible and adaptable way, and in some specific cases take the radical decision to move away from the coast.
2. As we aspire to increase the use of nature-based flood management solutions, we need new monitoring to assess the flood resilience offered by schemes and how they evolve over time.
3. We need to identify the mechanisms, spatial extent, and physical possible magnitude of low probability high impact extreme coastal flood events to inform emergency planning and calculate residual risk damages. We need to develop tools to quantify more accurately expected annual damages and event losses due to coastal sources, historically, today and into the future, to better inform the national threat level, considering uncertainty in the future projections of mean sea-level rise, changes in tide, storm surge and waves. We need a more-complete assessment of future changes in the wave- and storm surge-climate, storm tracks, and river discharge in estuaries, based on improved atmospheric models, to improve understanding of natural variability and better isolate possible long-term trends.

Top emerging issues:

1. Over the last decade there has been a move towards more-adaptive flood management. The Thames Estuary 2100 (TE2100) Plan was instrumental in introducing a novel, cost-effective approach to manage increasing flood risk by defining adaptation pathways that embraces uncertainty in sea-level projections and can cope with large ranges of changes if needed (Environment Agency, 2012). In response, the concepts and the assessment of adaptive pathways and approaches to valuing adaptive capacity are increasingly moving mainstream (McGahey and Sayers, 2008; Ranger *et al*., 2010; Brisley *et al*., 2016; Haasnoot *et al*., 2019) and are being considered elsewhere (e.g., in the Humber Estuary). At the same time adaptive management that aims to reduce future investment at the local scale is being implemented successfully (Creed *et al*., 2018). The Department for Environment, Food & Rural Affairs (Defra) has funded three Pathfinder projects located in Yorkshire, the South West and the Oxford Cambridge arc region, with the aim to raise

awareness of the actions homeowners and businesses can take at a local scale to make their homes more resilient to flooding.

2. There is an increased realisation that it is unrealistic to continue to promote a 'Hold the Line' policy for significant lengths of the coastline based on a benefit-cost ratio (Committee on Climate Change, 2018, Sayers *et al*, 2022). Funding for these locations is thus unlikely and realistic plans to adapt to the inevitability of change are needed now. Any change to the coast will impact the source variables (e.g., could lead to changes in tides, surge and near-shore wave climates), so should be monitored.
3. A major issue, relating to 'Hold the Line' policies, is the many historical coastal landfill sites located in coastal areas (Brand *et al*., 2017). Where landfills are present, the shoreline is usually defended to protect the environment and people from hazards that may be realised if the landfill is flooded or eroded. Therefore, coastal landfill sites need to be protected, but this may be at odds with Shoreline Management Plans that recommend 'managed realignment' or 'no active intervention' (Beaven *et al*., 2020).

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