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Future of the Sea: Current and Future Impacts of Sea Level Rise on the UK

Foresight – Future of the Sea
Evidence Review

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Current and Future Impacts of Sea Level Rise on the UK

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Contents

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Executive Summary

- **Sea level rise increases coastal flooding and erosion**, creating risks for UK infrastructure, communities, businesses and natural capital. Coastal flooding is one of the top four priority risks for the UK Government, and estimated annual damages are £540 million. Sea level rise projections for the 21st century are very uncertain, generally ranging from around 25 cm to around 1 m (depending on greenhouse gas emissions and ranges of modelling uncertainties), with a few estimates consistent with 1.5–2.5 m.
- **Uncertainty in the Antarctic ice sheet response to climate change** is the largest driver of uncertainty concerning sea level rise during this century. The first study to estimate probabilities of sea level rise from rapid Antarctic ice losses, co-led by the UK, strengthens evidence for the lower end: median total sea level rise of around 70 cm, implying estimated annual damages of £1.3–1.5 billion in the 2080s under current adaptation. A high-profile 2016 study has mean Antarctic estimates consistent with 2 m total sea level rise, but with large uncertainties and no consensus on their reliability. The UK is in a strong position to reduce this uncertainty due to world-leading expertise.
- **The 2017 Climate Change Risk Assessment** is wide-ranging, but the underlying research may systematically underestimate coastal flood risks. Better understanding of coastal processes, correlated risks (floods and impacts connected across space, time, business, sectors or nations), indirect impacts (such as disruption), infrastructure exposure and vulnerability, and the impacts of population and demographic changes on risk, would increase confidence that risks are sufficiently assessed.
- **Risks can be reduced** with sea defences, coastline realignment, land-use planning, forecasting, and property-level protection. However, not all risks can be offset, increasingly so with sea level rise and population increase.
- **Response options** for risk management include improving data collection, understanding, and uptake. Exposure and vulnerability data are sparse in several areas such as infrastructure and wellbeing, and the co-benefits and negative impacts of adaptation are not well-quantified. Use of existing evidence on risk management is limited in key sectors across individuals, infrastructure, businesses and local authorities.

1. Introduction

Sea level rise increases the frequency and severity of coastal flooding and erosion, and coastal flooding is one of the top four priority risks for the UK Government and one of the top three for non-malicious risks (Cabinet Office 2015). Coastal flooding and erosion create risks and, in a small number of examples, opportunities for UK infrastructure, communities, businesses and natural capital.

1.1 Sea Level Rise

Sea level has risen globally by around 20 cm from 1901 to 2010, at an average rate of 1.7 mm per year (IPCC 2013). The rate has increased over this period and is currently 3.2 mm per year (Chambers et al. 2016). A recent estimate attributed around 70 per cent of sea level rise from 1970 to 2005 to human activities (Slangen et al. 2016). At present the largest contribution is, often surprisingly to non-experts, thermal expansion of the world's oceans: that is, the volume of water increasing simply due to warming (40 per cent of the increase from 1993 to 2015). The rest is from the better-known losses of land ice from glaciers (25 per cent) and the Greenland and Antarctic ice sheets (20 per cent), along with transfer from land water sources such as groundwater and snow (15 per cent), with the ice sheet contributions increasing during this period (Chambers et al. 2016). Changes in Arctic and Antarctic *sea ice* contribute very little to sea level rise, because floating ice does not add extra volume to the oceans when it melts (Shepherd et al. 2010).

Global sea level is expected to continue rising, but projections vary widely. The most recent assessments of the Intergovernmental Panel on Climate Change (IPCC) ranged from around 25 cm to 1 m during the 21st century, depending on the scenario of greenhouse gas concentrations and range of modelling uncertainties (see Box 2), with the largest projected contributions continuing to be from thermal expansion (30–55 per cent) followed by glaciers (15–35 per cent, deriving from up to 85 per cent of the present volume of glaciers outside Antarctica) (Church et al. 2013). A few individual projections are consistent with around 1.5–2.5 m (Church et al. 2013; DeConto and Pollard 2016), mostly due to much larger contributions from the Antarctic ice sheet, but there is lower confidence in these estimates. Local factors, such as ocean circulation and land uplift, modify regional sea level rise relative to the global mean, making it more or less severe in different parts of the UK. (For overviews of sea level science, see Rhein et al. 2013; Pugh and Woodworth 2014.)

1.2 Coastal Flood Risk

Coastal flooding in the UK occurs during storm surges, which are mainly caused by strong onshore winds, and the higher the tide at the time the more likely flooding will be (Pugh and Woodworth 2014). Large-scale fluctuations in weather also affect sea level variability: for example, the decadal-scale changes of the North Atlantic Oscillation influence sea level variability in the North Sea, though perhaps less so for the English section (Chen et al. 2014; Ezer et al. 2016), and the exact mechanisms are not well understood.

Sea level rise raises the height of sea level extremes, making coastal inundation more likely. In general, projected increases in coastal flooding are predominantly or entirely due to this sea level rise, rather than changes in storm surges (Humphrey and Murphy 2016) or large-scale weather patterns, though there are regional variations (e.g. projected storm surge increases in northern Europe: see Vousdoukas et al. 2017) and substantial uncertainties due to the challenges of modelling storms and trends in natural variability (e.g. Kirtman et al. 2013).

Probability of flooding is not the only aspect to consider, as risk also includes exposure and vulnerability. The impacts of a given flood event are expected to increase, unless – or in many cases, even if – additional adaptation measures are taken. This is principally due to increasing exposure: population, and the number and value of coastal assets. However, estimates of the total capital value of assets at risk in the UK from coastal flooding and erosion are not necessarily straightforward to locate or interpret (see Box 1).

Box 1: Estimating total assets at risk

A Parliamentary Office of Science and Technology (POST) briefing note states that “£120 billion worth of infrastructure and resources [are] at risk from coastal flooding and a further £10 billion … from coastal erosion" (POST 2010). These estimates derive from a report produced for Defra 16 years ago, which estimates the capital value of all assets at risk, in England and Wales only, at £132.2 billion from coastal flooding (of which 98 per cent is residential and commercial property and 2 per cent agricultural land, with £81.3 billion in the Thames region exposed to up to a 0.5 per cent annual chance of flooding) and an additional £7.7 billion at risk from coastal erosion (Defra 2001). In other words, the values in POST 2010 are underestimates and out of date. A still widely cited estimate of £150 billion (e.g. Haigh et al. 2015) also appears to derive from the 2001 report.

Hallegatte et al. (2013) estimate $45 billion worth of assets in London would currently be exposed to a 1 per cent annual chance of flooding with no protection, but recent estimates of the total UK assets at risk have not been located within the timeframe of this review.

However, these are estimates if no defences were constructed. The considerable assets in the Thames region, for example, are protected by the Thames Barrier, motivated by the 1953 storm surge that caused an estimated £1.2 billion losses at 2014 values (Wadey et al. 2015). More relevant, then, are estimates that account for existing defences, which are presented in this review.

1.3 Managing Coastal Flood Risk

Adaptation measures can reduce all three aspects of risk: reducing the probability of inundation, through defences and managed realignment of coastlines; reducing exposure, by limiting development in flood-prone areas; and reducing vulnerability, through improved flood forecasting and warning, or individuals, organisations and communities improving their own protection levels. Global action to mitigate climate change would also reduce the rate of sea level rise and therefore the increase in sea level extremes (and thus the probability of inundation) over the long term.

Sea level rise means existing coastal defences will become more difficult and expensive to maintain. If UK defences are maintained at current levels, coastal flood risks are expected to increase due to rising sea level, population and assets.

This review examines current risks of coastal flooding and erosion in the UK, and how these are predicted to change by the end of the century; sources of uncertainty and knowledge gaps, and response options. The UK Climate Change Risk Assessment (CCRA) 2017 commissioned research which generally presented impacts for all types of flooding combined (Sayers et al. 2015). For this review, the data were requested to analyse coastal flood risks separately, and the scenarios are re-interpreted here for comparison with other evidence. Uncertainties and knowledge gaps beyond the CCRA are also discussed. A review of this length cannot be exhaustive: the aims here are to present a snapshot of current coastal flood risk assessments from the 2017 CCRA (separately for the first time), and to describe illustrative themes and examples of current and future coastal flood risks to the UK under sea level rise, along with some possible responses.

2. Current and Projected Impacts

Evidence in this section is taken from Sayers et al. (2015, 2016; from here onwards referred to as Sayers et al.) report and data for the CCRA, or the relevant chapter of the CCRA itself (infrastructure: Dawson, R. et al. 2016; business: Surminski et al. 2016; communities: Kovats and Osborn 2016), except where otherwise stated.

Scientists make projections under different scenarios that aim to span a range of possible socio-economic futures. The current generation of scenarios used by the IPCC to inform policy makers are the Representative Concentration Pathways (RCPs), different concentrations of greenhouse gases and air pollutants named RCP2.6, RCP4.5, RCP6.0 and RCP8.5 for their increasingly large warming effects by 2100 (IPCC 2013). However, much of UK climate risk assessment is founded in the UK Climate Projections 2009 (UKCP09: http://ukclimateprojections.metoffice.gov.uk), a comprehensive suite of projections for climate change and its impacts that use an older set of scenarios known as SRES (Special Report on Emissions Scenarios). UKCP09 was a large, complex, world-leading project to assess the uncertainties of climate change, and updated projections using the new RCPs will only be available from late 2018 (see section 4). Sayers et al. use three scenarios based on UKCP09, which are redescribed for this evidence review (see Box 2: Scenarios).

This section describes current estimated impacts and some broad themes from projections by Sayers et al. (statements below between *asterisks*); the latter are selected in order to illustrate the estimated long-term sensitivity of risks to sea level, population and adaptation in a simple way.

Box 2: Scenarios

The three scenarios presented by Sayers et al. for the CCRA (‘2 °C’, ‘4 °C’, and ‘H++’, – ‘High-plus-plus’), which are derived from UKCP09, are renamed for this evidence review as *Low–Medium*, *High* and *Extreme*, referring directly to the corresponding changes in global mean sea level from 1990 to 2100. This is a simpler and more useful framework for describing coastal flooding than the original temperature-based names, which referred to climate change more generally to describe other types of flooding. It allows the CCRA analysis to be compared here with the latest global mean sea level rise projections.

Note that the implications of each scenario for adaptation planning depend on the rate of sea level rise, which is uncertain; and that the scenarios are named here by *global* mean sea level rise, but the projections of UK impacts (by Sayers et al.) do incorporate *regional* patterns of sea level change.

The three sea level scenarios

Low–Medium – ca. **30 cm** global mean sea level rise from 1990 to 2100. This is at the low end of IPCC (2013) projected ranges for RCP2.6 (at least 66 per cent probability of being in the range 26–55 cm sea level rise from 1986–2005 to 2081–2100) and RCP4.5 (32–63 cm, similarly). It corresponds to strong mitigation, i.e. larger Intended Nationally Determined Contributions under the Paris climate agreement than at present (Climate Action Tracker Partners 2016).

High – ca. **60 cm** global mean sea level rise (1990–2100). This corresponds to mid-range projections for RCP8.5 (median 63 cm; 66 per cent or greater probability of being in the range 45–82 cm from 1986–2005 to 2081–2100), which has a similar trajectory to, or higher than, current greenhouse gas emissions.

Extreme – ca. **250 cm** global mean sea level rise (1990–2100). This has no equivalent within RCPs. This is the top end of the ‘H++’ scenario range proposed by UKCP09 for use in contingency planning where the consequences of rare events would be extreme (e.g. flooding of nuclear plants or other large-scale energy generating infrastructure; or reliability of the Thames Barrier; Environment Agency 2016a, 2016b). It was considered “very unlikely” but could not be “completely ruled out” (Lowe et al. 2009) and would require very high sensitivity of the ice sheets to climate change.

For each sea level scenario, we present their projections for the 2080s under the following population and adaptation scenarios:

- **A.** Current Population and Current Adaptation – Impacts only due to sea level rise.
- **B.** **High Population and Current Adaptation** – Additional impacts over (A) due to a 53 per cent increase in UK population by the 2080s, mostly in London and south-east England. Only affects risks for communities.
- **C.** **High Population and Enhanced Adaptation** – Reduction in impacts from (B) due to the highest level of adaptation considered by Sayers et al. (reducing flood probability, exposure, and vulnerability): see Sayers et al. (2015) Chapter 4, “Enhanced Whole System” scenario, for details.

2.1 Flood Events and Return Periods

There is no formal, national framework for recording the number and severity of flood events in the UK (Haigh et al. 2015). One recent estimate identified 47 coastal flood events from 1884 to 2013 in reports by the UK Met Office and the Centre for Ecology & Hydrology (Stevens et al. 2015). Another study identified 96 storm events from 1915 to 2014 that caused 310 high water events “likely to have resulted in coastal flooding”, based on tide gauge measurements supplemented with reporting from various sources (Haigh et al. 2015; database at surgewatch.org). Increases in reported flood events have been found to be explained by increased exposure (population growth and location) and reporting (Stevens et al. 2015).

The usual metric for describing flood probability is a return period or return level: a 1-in-100-year return period or level is where there is a 1-in-100 (i.e. 1 per cent) chance of that level being exceeded in a year. Sayers et al. define three bands of flood probability for their projections:

- **significant**: located in an area with 1-in-75 or greater annual chance of flooding;
- **moderate**: located in an area with between 1-in-75 and 1-in-200 annual chance of flooding;
- **low**: located in an area with less than 1-in-200 annual chance of flooding.

However, return periods are often misinterpreted. For example, the median waiting time is lower than the return period: for a 100-year return period, it is 69 years. One alternative is to give probabilities for longer periods than one year: for a 1-in-100-year event, there is a 9.6 per cent chance of at least one event of this magnitude in the next 10 years (see: Technical Annex below; Rougier 2017). If conditions change (e.g. with sea level rise), these values change.

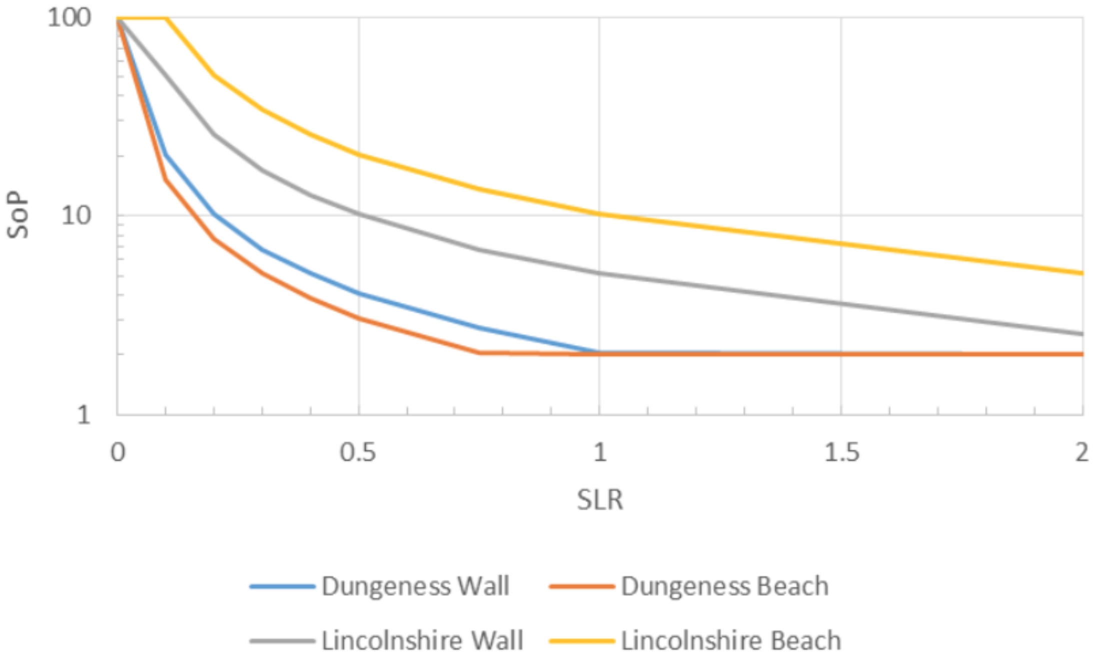


Figure 1. Standard of protection as a function of sea level rise: examples for two coastal locations and two defence types

Source: Sayers et al. 2015, Figure C1-1

Small increases in mean sea level rise (SLR) can lead to large decreases in the Standard of Protection (SoP: the frequency that a given defence is likely to be overwhelmed, expressed as a return period in years), due to the rapidly changing relationship between the two. Examples are shown in Figure 1 where, for example in the Lincolnshire area, a 0.5 m sea level rise leads to a 10-fold decrease in the Standard of Protection (from 1:100 to 1:10) provided by a wall. Sayers et al. (2015) estimate this is particularly the case for mid-west Wales and south-east England: by the 2080s, under *Low–Medium* sea level rise, a vertical wall with 1:100 years protection decreases to 1:5 and 1:8 years for the two regions respectively, worsening to 1:2 and 1:3 years under *High* sea level rise and 1:1 under *Extreme.* Embankments and shingle beaches are projected by Sayers et al. to provide better protection than vertical walls in most regions (e.g. 1:17 and 1:26 for mid-west Wales under *Low–Medium* sea level rise, and 1:7 and 1:10 for *High*), though sometimes worse protection for the south-east and south-west.

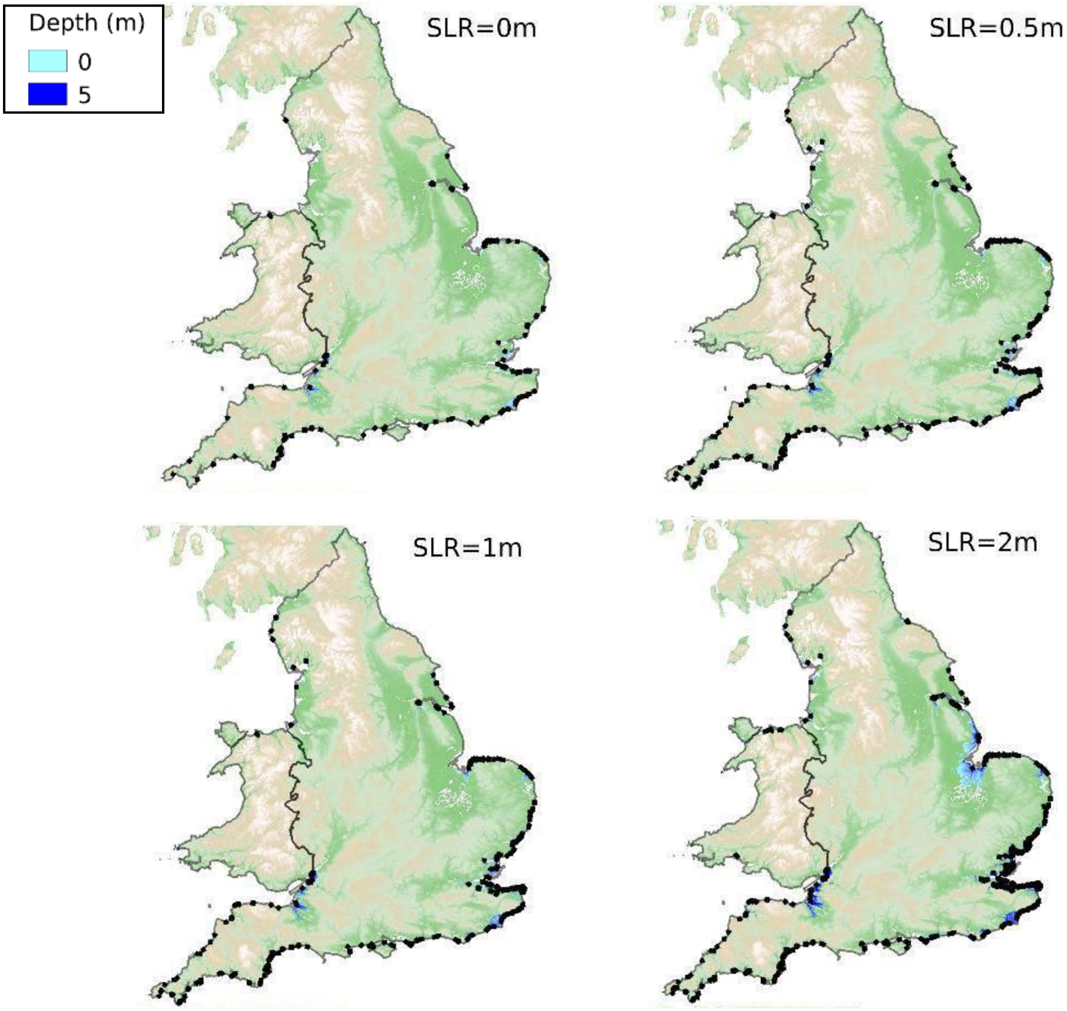


Figure 2. Increasing inundation with sea level rise

Temporary inundation extent (blue) under a 1:200 year return period tidal surge if vulnerable defences were lost, for different values of local sea level rise (SLR); England only; defences at risk are shown in black

Source: Sayers et al. (2015), Figure 7-4

If vulnerable coastal defences fail due to damage (e.g. erosion) by severe wave conditions, inundation area can significantly increase. Figure 2 shows how the inundation extent in England for a 1-in-200 return period event is estimated to increase with sea level rise if vulnerable defences were to be lost; Figure 3 shows the corresponding number of properties (residential or non-residential) at risk in England under 1 m sea level rise.

Uplift of the land, rebounding from loss of ice sheets after the last ice age, partly offsets sea level rise in northern areas (e.g. Lowe et al. 2009): England and Wales are projected to experience around 30 per cent higher sea level rise than mainland Scotland and NI under the *Low–Medium* scenario, and around 10 per cent higher under the *High* and *Extreme*. Ocean circulation changes also affect regional sea level rise (e.g. Howard et al. 2014).

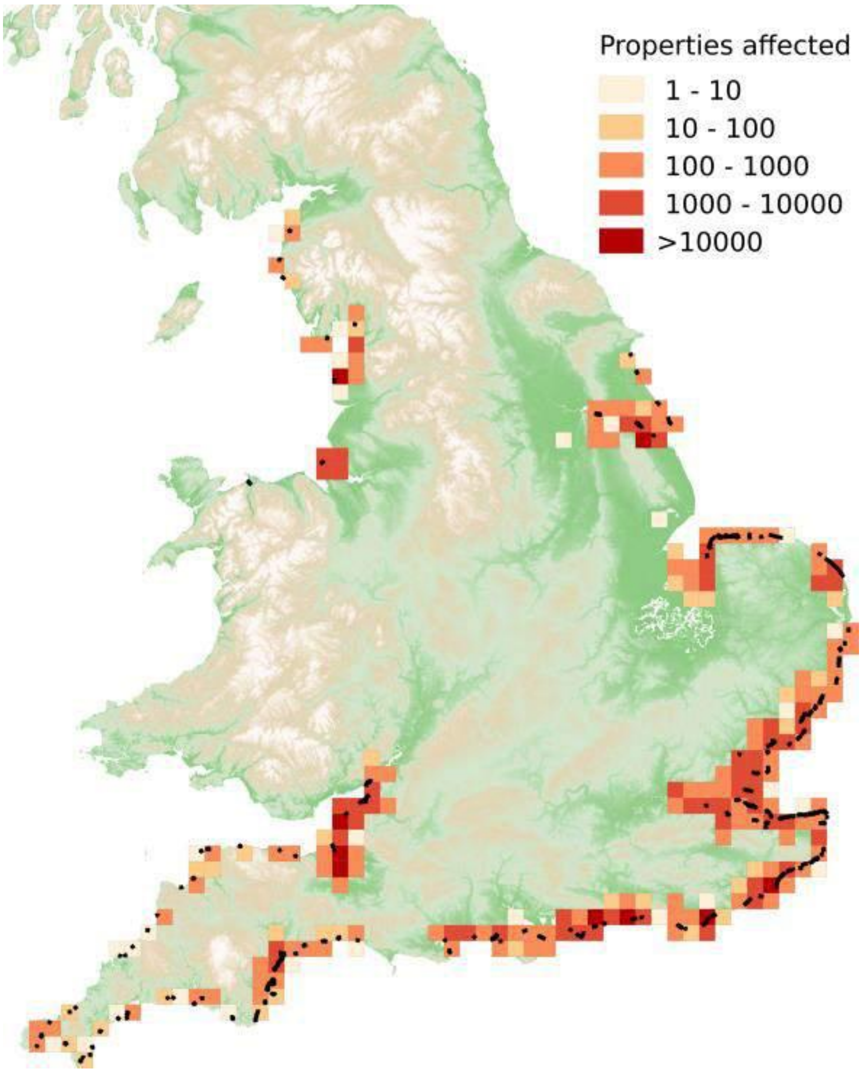


Figure 3. Properties with moderate or greater probability of flooding with 1 m sea level rise: number of properties (residential and non-residential) potentially affected by a future 1:200 year coastal surge under 1m local sea level rise, for England only

Squares are 10 km x 10 km

Source: Sayers et al. (2015), Figure 7-9

Sayers et al.'s estimates of current expected annual damages (EAD) and exposure to 'significant' (1-in-75) probability of flooding in the present day and 2080s are presented for 24 metrics in Tables 1 and 2; these and other evidence are described below. Uncertainties are not quantified for these projections, so this should be considered when interpreting their results – this is particularly important for costs, which are difficult to quantify. However, the analysis by

Sayers et al. is quite comprehensive and can be considered the best central estimates available.

Table 1. Non-residential risks: expected annual damages (EAD), and various aspects of non-residential property, infrastructure and natural capital at 'significant' (1-in-75 or greater) annual probability of flooding

Sea level rise	Current	Low-Medium		High		Extreme	
Population	Current	A Current	C High	A Current	C High	A Current	C High
Adaptation level	Current	Current	Enhanced	Current	Enhanced	Current	Enhanced
Non-residential EAD (direct)	£190m	£300m (58%) S	£220m (17%) S	£540m (182%) S	£460m (141%) S	£690m (261%) S	£630m (231%) S
Non-residential properties	79,000	100,000 (33%) S	94,000 (19%) S	110,000 (38%) S	100,000 (29%) S	110,000 (38%) S	100,000 (29%) S
Power stations	6.0	7.0 (17%) SASS	6.5 (9%) SASS	8.0 (33%) SASS	8.2 (36%) SASS	8.0 (33%) SASS	8.2 (36%) SASS
Substations	86	120 (44%) SASS	110 (23%) SASS	130 (48%) SASS	120 (41%) SASS	130 (48%) SASS	120 (41%) SASS
Railway stations	51	61 (19%) S	54 (5%) ASSS	63 (24%) S	57 (12%) S	63 (24%) S	57 (12%) S
Railway length	360 km	450 km (27%) S	410 km (15%) S	490 km (36%) S	460 km (29%) S	500 km (39%) S	470 km (31%) S
Major road length	630 km	890 km (42%) S	840 km (33%) S	1,000 km (62%) S	990 km (57%) S	1,000 km (63%) S	990 km (57%) S
Water/wastewater treatment sites	47	56 (18%) S	46 (-3%) SSAS	56 (20%) S	51 (8%) SSAS	56 (20%) S	51 (8%) SSAS
Landfill sites	35	41 (17%) S	38 (7%) S	43 (22%) S	39 (12%) S	43 (22%) S	39 (12%) S
Schools	120	160 (33%) SSAS	140 (20%) SSAS	170 (45%) SSAS	160 (36%) SSAS	170 (45%) SSAS	160 (36%) SSAS
Hospitals	5.0	6.0 (20%) S	4.2 (-15%) ASSS	5.0 (0%) ASSS	4.2 (-15%) ASSS	5.0 (0%) ASSS	4.2 (-15%) ASSS
Emergency services	42	61 (45%) S	57 (36%) S	72 (72%) S	69 (65%) S	73 (73%) S	70 (66%) S
GPs surgeries	77	100 (35%) S	87 (14%) S	100 (35%) S	93 (21%) S	100 (35%) S	93 (21%) S
Care homes	65	100 (54%) S	85 (31%) S	110 (63%) S	97 (49%) S	110 (63%) S	97 (49%) S
SPA area (ha)	49,000	60,000 (22%) SSAS	57,000 (17%) ASAS	64,000 (31%) SSAS	62,000 (26%) SSAS	65,000 (33%) SSAS	62,000 (28%) SSAS
SAC area (ha)	32,000	39,000 (20%) S	37,000 (15%) ASAS	42,000 (30%) S	39,000 (23%) ASAS	43,000 (33%) S	40,000 (26%) ASAS
Ramsar area (ha)	45,000	53,000 (18%) SSAS	50,000 (11%) ASAS	56,000 (24%) SSAS	53,000 (18%) ASAS	57,000 (26%) SSAS	54,000 (20%) ASAS
BMV agricultural land area (ha)	130,000	180,000 (37%) S	160,000 (25%) S	180,000 (39%) S	170,000 (31%) S	180,000 (39%) S	170,000 (31%) S

Current values are shown in the first column, and future projections in the following columns (absolute values and percentage change relative to present day; decimal places are due to interpolations in the original analysis; percentages are calculated from unrounded numbers so may differ from absolute changes); letters S, P, A indicate which of sea level, population or adaptation contributes most for England, Scotland, Wales and NI respectively (single: all nations)

See Box 2 for sea level, population and adaptation scenario details

Table 2. Community risks: total and residential-only expected annual damages (EAD), and the number of people and properties affected at ‘significant’ (1-in-75 or greater) annual probability of flooding

Sea level rise	Current	Low-medium			High			Extreme		
Population	Current	A Current	B High	C High	A Current	B High	C High	A Current	B High	C High
Adaptation level	Current	Current	Current	Enhanced	Current	Current	Enhanced	Current	Current	Enhanced
Total damages	£540m	£830m (53%) S	£800m (48%) S	£600m (11%) ASSS	£1,500m (176%) S	£1,300m (142%) S	£1,200m (127%) S	£1,900m (252%) S	£1,900m (256%) S	£1,700m (219%) S
Residential property EAD (direct)	£130m	£190m (46%) S	£170m (32%) ASPS	£130m (-1%) ASAA	£340m (162%) S	£230m (79%) ASSS	£260m (102%) ASSS	£430m (233%) S	£440m (242%) S	£390m (196%) S
Number of people affected	270,000	370,000 (37%) S	730,000 (171%) PSSS	450,000 (66%) PSSS	390,000 (44%) S	750,000 (179%) PSSS	500,000 (83%) PSSS	390,000 (44%) S	750,000 (178%) PSSS	500,000 (84%) PSSS
Number of people affected in deprived areas	63,000	88,000 (39%) S	180,000 (185%) PSPS	100,000 (61%) PSPS	92,000 (46%) S	180,000 (193%) PSPS	110,000 (80%) PSPS	92,000 (46%) S	180,000 (192%) PSPS	110,000 (80%) PSPS
Residential properties	220,000	310,000 (41%) S	550,000 (149%) PSPS	380,000 (72%) PSPS	310,000 (43%) S	560,000 (154%) PSSS	400,000 (83%) PSSS	310,000 (43%) S	560,000 (153%) PSSS	400,000 (83%) PSSS
Deprived households	29,000	40,000 (38%) S	79,000 (172%) PSPS	45,000 (57%) PSPS	42,000 (44%) S	81,000 (180%) PSPS	51,000 (76%) PSPS	42,000 (44%) S	81,000 (180%) PSPS	51,000 (76%) PSPS

Current values are shown in the first column and future projections in the following columns; absolute values and percentage change relative to present day; decimal places are due to interpolations in the original analysis; percentages are calculated from unrounded numbers so may differ from absolute changes; letters S, P, A indicate which of sea level, population or adaptation contributes most for England, Scotland, Wales and NI respectively (single: all nations)

See Box 2 for sea level, population and adaptation scenario details

2.2 Expected Annual Damages (EAD)

Expected Annual Damages are the mean economic damages over all possible flood return periods (averaging over small damages from frequent flood events and large damages from rare events); future damages are reported here at 2014 prices. Sayers et al. estimate current EAD from coastal flooding to be £540 million, around 40 per cent residential and 60 per cent non-residential. The majority (£320m) is direct damage to properties and economic assets; the remainder is an approximate estimate of indirect damages (disruption of economic networks and related activities) that assumes they are 70 per cent of direct damages. Costs are disproportionately high, relative to national population proportions, for residential properties in Wales and England, and for non-residential properties in Wales and Scotland.

Flood damages could double or triple, even with high adaptation, under the scenarios explored by Sayers et al. (Tables 1 and 2). Expected Annual Damages are estimated to more than double by the 2080s in the *High* sea level scenario (130–180 per cent increase to £1.2m–£1.5m) and more than triple in the *Extreme* (220–260 per cent increase to £1.7m–£1.9m), even under *Current Population* or *Enhanced Adaptation*. Non-residential damages increase by a larger proportion than residential.

However, adaptation could offset damages if sea level rise is low (Table 2). *Enhanced Adaptation* limits the increase in total and residential damages to around 10 per cent of present estimates under *Low–Medium* sea level rise (£60m increase in total damages; negligible increase in residential). This is partly because higher population (counter-intuitively) decreases estimated future damages relative to present population, which is likely due to more-effective control of surface water run-off for additional new build properties (Sayers 2017).

2.2.1 Infrastructure

Individual sub-sectors are outlined, followed by broad themes from Table 1.

Ports – Ports are particularly at risk. The UK has 52 major ports, and the industry carries 95 per cent of incoming freight by volume (75 per cent by value) and 40 million passenger journeys per year. Disruption can have substantial consequences due to cargo specialisation and impacts on local businesses: Immingham near Grimsby, for example, which specialises in petro-chemicals and biomass fuel, ceased operations for a number of days after flooding in December 2013. A recent comprehensive assessment of maritime disruptions from 1950 to 2014 using news records identified 11 moderate to severe events due to storm surges (Adam et al. 2016). Port flood events are decreasing due to improved defences and forecasting, though financial losses arise from pre-emptive closures.

Projections – Sea level rise exceeding 50 cm by 2080 has been highlighted as a particular concern for UK ports. This is likely to occur, as the IPCC (2013) assesses that, under the lowest scenario (RCP2.6), there is up to a 1-in-6 chance of sea level exceeding 55 cm by around 2090, and for the highest scenario (RCP8.5) at least a 5-in-6 chance of exceeding 45 cm (see ranges in Box 2: Scenarios).

Energy – All of the UK's 19 nuclear plants, 12 oil and gas terminals and six oil refineries are situated on the coasts, along with all the major fossil-fuel power stations of Wales, Scotland and Northern Ireland. A 160-year life cycle for nuclear plants means long-term planning is essential (e.g. Wilby et al. 2011). Flooding causes longer disruptions to electricity stations than other weather-related incidents, and sub-stations for transmission and distribution are generally less protected than power stations. Sayers et al. estimate 86 major electricity sub-stations and six major generation stations are in areas with 'significant' (1-in-75 or greater) annual chance of flooding, with a total of around 310 in areas with 'significant' or 'moderate' (1-in-200 or greater) annual chance.

Projections – The 2012 Climate Change Risk Assessment found 12 of the UK's 19 nuclear plants would be at risk of erosion or coastal flooding by the 2080s without protection. Plants are required to be defended up to a 1 in 10,000 year event, but there are deep uncertainties about such rare events. For example, after the 2011 Fukishima Daichii disaster, a review revealed the shingle defences of Dungeness B were "not as robust as previously thought". Several stages of additional sea defences were added, including a two-month site closure to review procedures (ONR 2013; 2014); Dungeness is not a proposed site for Nuclear New Build.

Transport and communications – Sayers et al. estimate 15 per cent of the UK major road network length is in areas with ‘significant’ or ‘moderate’ annual chance of coastal flooding (5 per cent ‘significant’) and 4–5 per cent of the UK railway network length and stations are in areas with ‘significant’ or ‘moderate’ annual chance (2 per cent ‘significant’). If coastal defences fail it can be highly disruptive. In 2014, storms damaged the sea wall at Dawlish (on one of the most expensive stretches of line to maintain: £2.1m/year, including repairing one-off events and compensation), severing the main rail connection to south-west England for two months with estimated direct costs of £50m (Dawson, D. et al. 2016); the link between Harlech and Barmouth was closed for four months.

Information and communications technology (ICT) infrastructure is generally considered to be relatively resilient and capable of adapting to future change, because it is a networked system with redundancy, diversity and short equipment lifetimes. However ICT infrastructure can be vulnerable to flooding, erosion and saline corrosion, particularly at the edges of networks including remote areas.

Projections for transport – UK railway infrastructure is expected to be particularly at risk in the future. According to the CCRA:

> Systemic adaptation is not strongly evident across the railway network and there is a significant legacy challenge of ageing infrastructure, with both the industry and regulator recognising that historic investment in ageing structures has been insufficient to deliver acceptable levels of risk in the long term. *There is a significant backlog that will require sustained investment over the next 40 – 50 years to clear.* Models have been developed by Network Rail to forecast the amount of investment and volume of renewals required for civil engineering structures, including earthworks, tunnels, bridges and sea walls. However, *these models do not account for projected changes in climate* but instead assume that the weather experienced in the future will be similar to what is [*sic*] has been in recent years. In the regulator’s assessment, *Network Rail has not sufficiently embedded climate resilience* into specifications for the design of its assets, or in the standards the company sets for asset maintenance and renewal.
>
> (Dawson, R. et al. 2016, 52, emphasis added)

Under *Current Adaptation*, the length of railway network in areas with ‘significant’ (‘significant’ or ‘moderate’) annual chance of flooding is projected to increase by 26–39 per cent (9–11 per cent) across sea level and population scenarios; *Enhanced Adaptation* reduces this increase to 15–31 per cent (1–3 per cent), i.e. it is particularly effective for moderate flood probability. The number of stations at ‘significant’ (‘significant’ or ‘moderate’) probability is projected to increase by 19–24 per cent (20–21 per cent); with *Enhanced Adaptation* this reduces to half or fewer, 5–12 per cent (9–10 per cent). The length of rail network in England at risk of erosion is projected to increase from 11 km to 62 km by 2100.

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 (£6.9–£8.7m per year, including over £1m compensation – Dawson, D. et al. 2016). By 2100, this number is projected to increase to 84–120 days per year under global mean sea level rise of around 55–76 cm (similar to the *High* scenario), and 270 days (i.e. three-quarters of the year) under the *Extreme* 250 cm sea level scenario (Dawson, D. et al. 2016).

Despite this, Network Rail estimate it would be more expensive to reroute the line (£470m–£3.1bn).

Under *Current Adaptation*, the length of road network in areas with ‘significant’ (‘significant’ or ‘moderate’) annual chance of flooding is projected to increase by 42–63 per cent (15–17 per cent) across sea level and population scenarios; with *Enhanced Adaptation* this reduces somewhat to 33–57 per cent (6–9 per cent). The length of major roads in England at risk of erosion is projected to increase from 1 km to 12 km by the 2100s.

Water, waste, health and social care – Sayers et al. estimate that areas under ‘significant’ (‘significant’ or ‘moderate’) annual chance of coastal flooding include around 47 (130) water and wastewater treatment sites, 20 (40) landfill sites, 5 (30) hospitals, 42 (140) emergency services, 77 (370) GP surgeries, 65 (380) care homes, and 120 (440) schools.

Sea defences – Sea defences themselves are at risk, including hard and soft shoreline structures (engineered and natural: see section 2.2.4) and tidal barriers (also known as flood or storm surge barriers). England's coastline is 4,500 km, of which nearly a quarter has coastal flood defences. The UK has two of the world’s 18 storm surge barriers – across the River Thames and a much smaller barrier across the River Hull, closing an average of two and 12 times per year respectively (Mooyaart and Jonkman, 2017) – with a further small barrier being built at Ipswich. The Thames Barrier was closed an “exceptional” 50 times in 2013/14, the maximum recommended number, but this was predominantly due to very heavy rainfall (i.e. high river flow), and no statistically significant trend in past closures has been detected (Environment Agency, 2016b). In England, Wales and some parts of Scotland, non-statutory Shoreline Management Plans (SMPs) describe future plans for defences: ‘advance the line’, ‘hold the line’, ‘managed retreat’ or ‘no active intervention’ (Figure 4, left). Sayers et al. identify the 11 per cent (110 km) of defences they judge most vulnerable to failure due to the relatively low height of their base above the water (Figure 4, right). Around 40 per cent of the English coast is liable to erosion, of which one-fifth is defended.

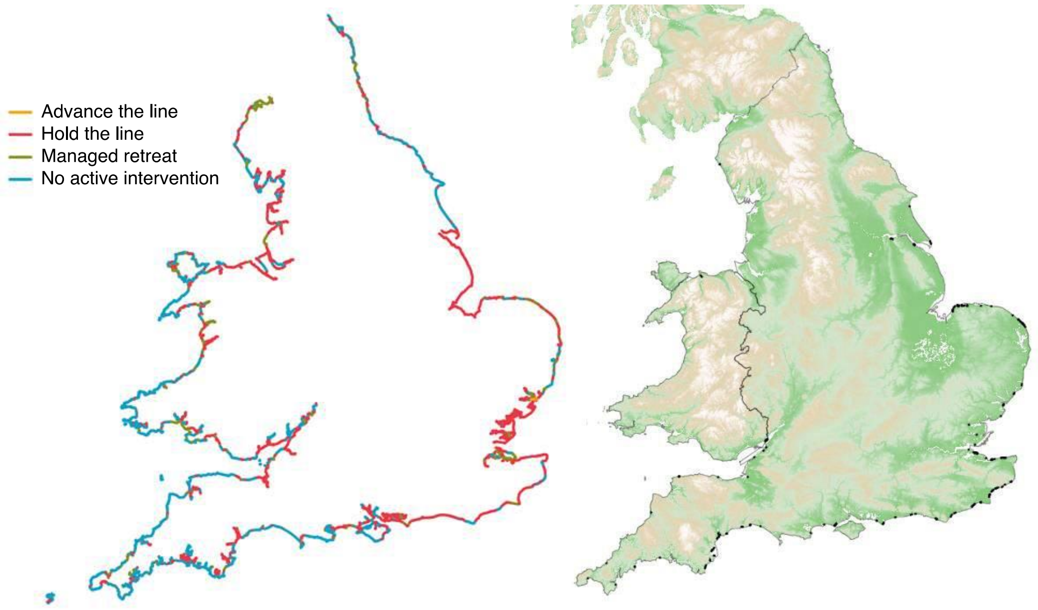


Figure 4. Comparing Shoreline Management Plans (SMPs) and vulnerable defences; left: SMP options for 2010–2030 in England and Wales; right: estimated vulnerable defences with no sea level rise, shown as black lines, for England only

Source: Sayers et al. (2015), Figure 7-2

Projections – Sayers et al. project the length of coastal defences 'highly vulnerable' to failure would increase by around 70 per cent under 50 cm local sea level rise (similar to the *High* scenario), with the number of properties affected if these were lost rising disproportionately by around 160 per cent. Under the *Extreme* scenario, the length of defences and number of properties affected are projected to increase by 210 per cent and 490 per cent respectively. In all cases around 70 per cent of the properties are residential.

Overall, adaptation could offset some significant infrastructure risks, particularly if sea level rise is low (Table 1). *Enhanced Adaptation* limits the number of railway stations, hospitals, and water/waste treatment and landfill sites at significant annual chance of flooding to within around 10 per cent of present day, and also the number of power stations, under *Low–Medium* sea level rise. Sample sizes are small so uncertainties are relatively large, particularly for hospitals and power stations.

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 is predicted to extend to around 2070 (Environment Agency 2016b).

2.2.2 Businesses

Uptake of flood protection and adaptation measures is relatively low, with small businesses particularly at risk: only a quarter of businesses with fewer than 10 employees have continuity plans for extreme weather. However, economic activity itself tends to be displaced or postponed rather than lost. There are also opportunities, as most adaptation action is expected to be delivered by the private sector in developing climate-resilient products and services. Sayers et al. estimate direct EAD to all non-residential properties as £190m, with 220,000 properties in areas with 'significant' or 'moderate' annual chance of flooding, of which 80,000 are 'significant' (Table 1): this includes all building assets defined as non-residential, including businesses, police stations, schools and hospitals.

Projections – Under *Current Adaptation*, the number of non-residential properties in areas with 'significant' ('significant' or 'moderate') annual chance of flooding is projected to increase by 33–38 per cent (9–10 per cent) across sea level and population scenarios; *Enhanced Adaptation* reduces this to 19–29 per cent (–2 to –3 per cent), i.e. it is particularly effective for moderate probability.

2.2.3 Communities

According to European Commission statistics cited in the CCRA, over one-third of the UK population lives within 5 km of the coast (defined as Mean High Water level) and nearly two-thirds within 15 km. Around 7 million are estimated in the Global Rural–Urban Mapping Project to live below 10 m elevation (Nicholls 2017). The 1953 storm surge is estimated to have caused 475 deaths (Adam et al. 2016), although in general it is difficult to attribute deaths to flood events. Sayers et al. estimate direct EAD to residential properties as £130m, and the following to be in areas with 'significant' ('significant' or 'moderate') annual chance of flooding: 270,000 (1,070,000) people, of which 23 per cent (21 per cent) in deprived areas, and 220,000 (540,000) residential properties, of which 13 per cent (19 per cent) are deprived households.

Projections – *Significant risks to communities could double, unless population increase is low or adaptation high* (Table 2). Under *High Population* and *Current Adaptation*, the numbers of people and residential properties in areas with significant annual chance of flooding more than double under all sea level scenarios (170–180 per cent increase, to 730,000–750,000), slightly more so for those in deprived areas (190 per cent increase, to 180,000).

Adaptation may not offset increase in significant risk due to population increase, if the population increase is high (Table 2). In contrast to predictions for residential damages, *High Population* makes it harder to limit the number of people and properties at substantial risk: *Enhanced Adaptation* does not offset the risk due to increased population, even under low sea level rise (*High Population, Enhanced Adaptation* numbers affected are systematically higher than *Current Population and Adaptation*). Figure 5 shows the limited effectiveness of *Enhanced Adaptation* on reducing the number of properties in areas with significant annual chance of flooding under low population growth even for *Low–Medium* sea level rise (figures were not available for *Current* or *High Population*).

In terms of erosion, the Environment Agency estimates 700 properties in England could be lost over the next 20 years and about 2,000 in the next 50 if current defences are maintained (Surminski et al. 2016). If defences were abandoned, losses would be much greater: for example, around 500 properties in North Norfolk would be threatened (Dawson et al. 2009; Koukoulas et al. 2005).

However, risks to communities are broader than simply inundation and erosion. Projections of increased flood risk, and resultant planning of coastline realignment, can lead to complex and emotive stakeholder discussions and may increase the risk of economic blight. The viability of some communities may be threatened by loss or relocation due to managed or non-managed realignment.

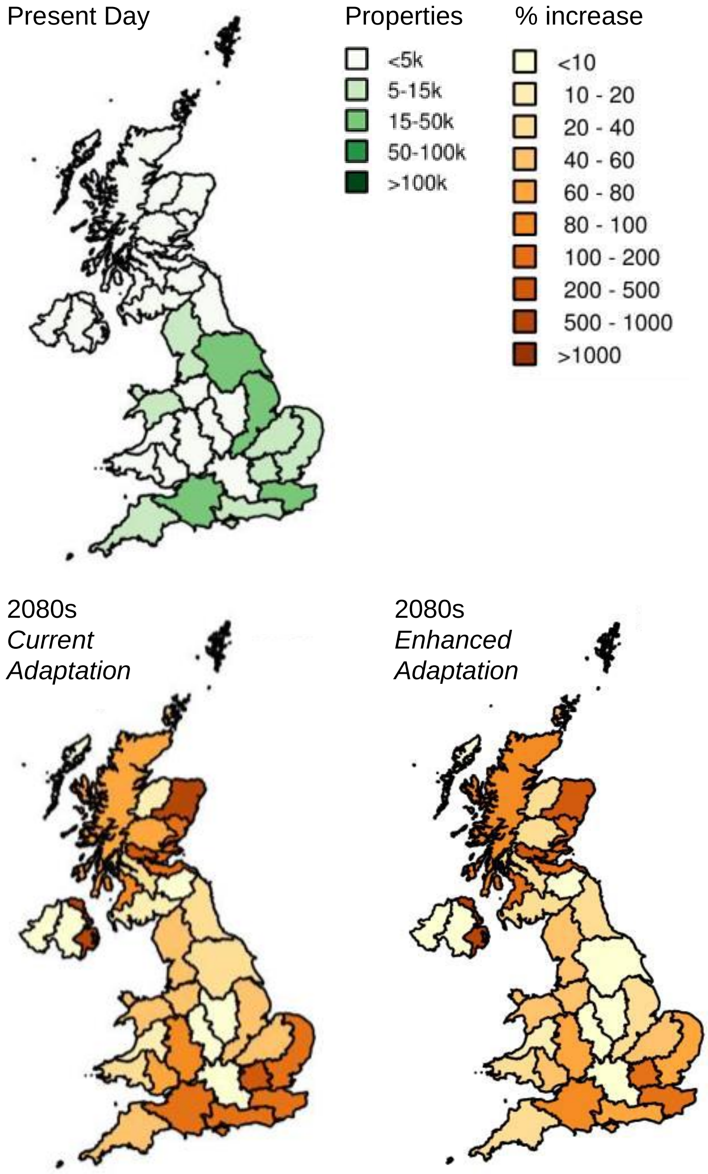


Figure 5. The influence of adaptation on coastal flood risk to properties for low sea level rise and low population increase

Top: Number of residential properties exposed to flooding more frequently than 1:75 years in the present day; bottom: percentage increase in properties for (left) *Current Adaptation* and (right) *Enhanced Adaptation* levels under *Low–Medium* sea level scenario and low population growth

Source: Sayers et al. (2015), Figure 6-16

2.2.4 Natural Capital

Natural capital at risk includes agricultural land, ecosystems, as well as flood defences such as sand dunes, saltmarsh and sediment. One example is machair, a unique grassland ecosystem along the Atlantic coasts of Scotland and Ireland, which is particularly exposed by its low-lying elevation (Ford et al. 2013). Sayers et al. estimate 130,000 hectares of Best and Most Versatile (BMV) agricultural land are currently in areas with ‘significant’ annual chance of flooding, about the size of Greater Manchester, as is the same total area of Special Areas of Conservation (SACs), Special Protection Areas (SPAs) and Ramsar sites (wetlands of international importance) (Table 1). The areas estimated to have ‘significant’ or ‘moderate’ annual chance of flooding are 380,000 hectares of BMV agricultural land and 170,000 hectares of SAC, SPA and Ramsar sites.

Projections – Areas with significant annual chance of flooding are projected to increase by around one-quarter to one-third for all scenarios: areas of BMV agricultural land increase 37–39 per cent under *Current Adaptation* across different sea level scenarios, and by slightly less, 25–31 per cent, under *Enhanced Adaptation*; the areas of other types of natural capital at risk increase less than agricultural land, by 18–33 per cent under *Current Adaptation* and 11–28 per cent under *Enhanced Adaptation* (Table 1).

2.2.5 Global Impacts

Global coastal flooding has implications for the UK, for example through immigration, overseas aid, trade and supply chains. UK trading partners such as China, India and the United States are particularly vulnerable to coastal flood damages. Modern tide gauge data show sea level has risen in all the British Overseas Territories since the early 1990s; territories thought to be particularly vulnerable to future sea level rise include Gibraltar, the Falkland Islands and St Helena (due to harbour infrastructure); the Caribbean (due to sandy beaches); and the British Indian Ocean Territory (due to corals) (Woodworth and Hibbert 2015).

Around 11 per cent of the world’s population live within 10 m of sea level (Neumann et al. 2015). As for the UK, estimates of vulnerability and associated costs are uncertain. One study estimates 15–50 per cent of this number are exposed to 1-in-100 or greater annual chance of flooding, along with US $3–11 trillion of assets (Hinkel et al. 2014). Many cities in developing countries are at risk; among those with highest population exposed and substantial relative vulnerability (ratio of average annual losses to the city’s gross domestic product) are cities in India (Mumbai and Kolkata, total 4.7 million exposed), China (Guangzhou and Tianjin, 3.7 million), Vietnam (Ho Chi Minh City and Hai Phong, 2.7 million), Thailand (Bangkok, 0.9 million), and Bangladesh (Dhaka, 0.8 million) (Hanson et al. 2011; Hallegatte et al. 2013).

Projections – Hinkel et al. (2014) project that under constant adaptation up to 3 per cent of the global population would be flooded annually in 2100 under RCP2.6 and up to around 5 per cent under RCP8.5, with annual damages of up to 5 per cent and 9 per cent of global GDP respectively. Costs of enhanced protection (via defences and/or relocation) are far lower than damages avoided, highlighting that global adaptation will be widespread. Neumann et al. (2015) project that the population living within 10 m of sea level could double to 1.4 billion by the 2060, but sea level rise is not included in this: the dominant driver is world population increase, along with a slight increase in the fraction living along the coasts. Hanson et al. (2011) estimate that under 50 cm global mean sea level rise by 2070 (similar to the *High* scenario), sea level contributes about a quarter to increased population exposure in coastal cities, and Hallegatte et al. (2013) project similar estimates for relative vulnerability.

2.2.6 Long-Term Impacts

This review focuses on sea level rise this century. However, not only is sea level expected to continue rising well beyond 2100, but current greenhouse gas emissions are expected to affect sea level for hundreds or thousands of years due to the very long timescales of ice sheets responding to climate change. If the global warming projected for this century is sustained, it could lead to irreversible loss of the Greenland ice sheet:

> There is high confidence that sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than about 1°C (low confidence) but less than about 4°C (medium confidence) global mean warming with respect to pre-industrial. (IPCC 2013)

How long this warming would need to be sustained is also uncertain. Since the IPCC (2013) assessment, there is also evidence to suggest irreversible ice loss has initiated in part of the Antarctic ice sheet; it is not yet clear the degree to which humans have contributed to this, and there remain large uncertainties about the potential speed and magnitude of further losses in this and following centuries.

3. Sources of Uncertainty, and Knowledge Gaps

3.1 Observations

In the UK, maintenance and support of the 44 tide gauges of the UK National Tide Gauge Network has since April 2016 been subcontracted by the Environment Agency. In the British Overseas Territories, Woodworth and Hibbert (2015) show tide gauge records are not coherently managed or complete: for the 14 territories, only five have tide gauges operated by the UK, and six have no long records within 100 km.

3.2 Antarctic Contribution to Sea Level Rise

Uncertainty in ‘ice sheet sensitivity’, used here to mean the difference between the *High* and *Extreme* scenarios, is assumed to be dominated by Antarctica rather than Greenland. This is based on evidence since UKCP09 and the IPCC (2013) indicating that collapse of part of the West Antarctic ice sheet is underway (Rignot et al. 2014; Favier et al. 2014), along with the wide range of projections for such a collapse (IPCC 2013, and Box 3), and the relatively narrow range of Greenland projections. This is particularly true for the UK, due to the (counter-intuitive) fact that northern hemisphere sea level is more affected by Antarctica than Greenland due to compensating gravitational effects on local sea level when ice is lost from the latter. Uncertainty in Greenland projections is relatively more important for areas in the low latitudes and Southern Hemisphere, including British Overseas Territories.

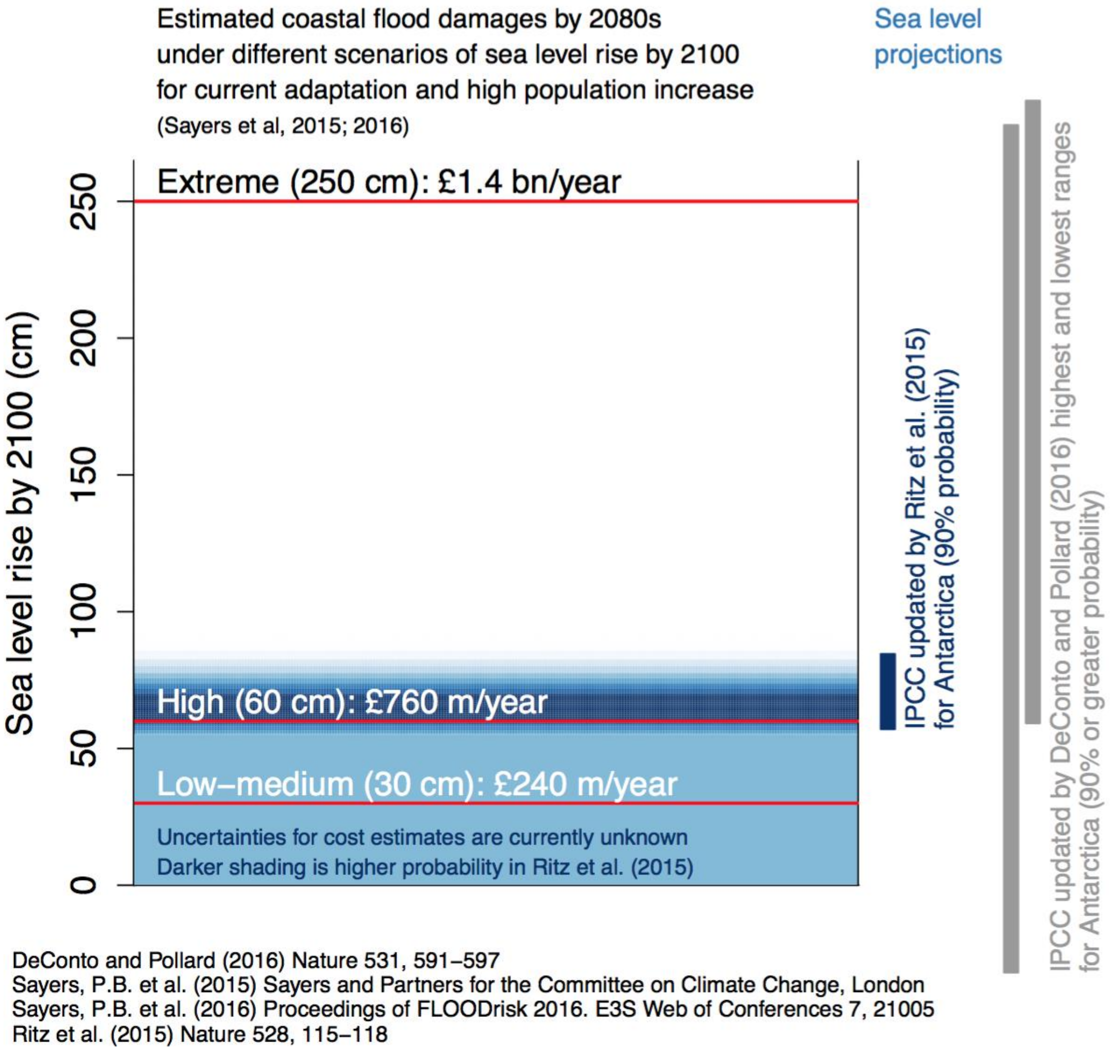
Current Antarctic ice sheet projections require careful interpretation (Box 3: Antarctic contribution to sea level rise). The highest would imply national safety margins for defences (Quante and Colijn 2016) were no longer sufficient, but detecting acceleration in sea level rise is challenging. The flexible, iterative Thames Estuary 2100 (TE2100) plan includes sea level monitoring and could adapt to the *Extreme* scenario (Environment Agency 2016b).

Box 3: Antarctic contribution to sea level rise

This review assesses recent evidence for the plausibility of *Extreme* sea level rise (250 cm by 2100) resulting from Antarctic ice sheet collapse initiating this century. The main estimate (Figure 6: dark blue bar) uses the IPCC (2013) RCP8.5 projection updated with a newer estimate for Antarctic collapse by Ritz et al. (2015). A key novel aspect of that study is the estimation of probabilities (dark blue shading). Combining these gives a median of 67 cm by 2081–2100, slightly higher than the *High* scenario (ca. 60 cm), with a 1-in-20 chance of exceeding 85 cm and a negligible chance of the *Extreme* scenario. Ritz et al. use a simplified model, but their results are consistent with the IPCC (2013) and individual projections by state-of-the-art models (Favier et al. 2014; Cornford et al. 2015).

A high-profile study by DeConto and Pollard (2016) estimated four "possible envelopes of behaviour" for Antarctica, of which the central values of two envelopes exceeded 1 m – around three times higher than the Ritz et al. (2015) maximum. However, there is no consensus about their reliability, because the process for rapid, large-scale ice losses they propose ('cliff failure') is highly simplified and does not account for mitigating factors that may be substantial. Furthermore, the error bars are so large that probabilities are effectively unconstrained: statistically they are consistent with up to 5 per cent probability from Antarctica of sea level *fall* of 90 cm and also sea level *rise* of 230 cm (Figure 6: grey bars, combined with IPCC for non-Antarctic contributions; see Technical Annex for statistical interpretation).

Therefore although DeConto and Pollard (2016) could be interpreted as supporting the possibility of the *Extreme* (H++) sea level rise scenario of 250 cm by 2100 (Figure 6: grey bars extend above *Extreme* line), even allowing up to 18 per cent probability of exceeding it (see Technical Annex), the literature does not currently indicate this finding is robust. Unless further evidence is found to support very rapid Antarctic ice losses this century, the *Extreme* scenario is considered (by this author and, in her view, the majority of the ice sheet expert community) highly unlikely.



DeConto and Pollard (2016) Nature 531, 591–597
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Sayers, P.B. et al. (2016) Proceedings of FLOODrisk 2016. E3S Web of Conferences 7, 21005
Ritz et al. (2015) Nature 528, 115–118

Figure 6. Infographic – coastal flood damages and sea level projections: increase in expected annual damages relative to present day (£540 m/year) estimated by Sayers et al. for the UK Climate Change Risk Assessment 2017, and IPCC (2013) sea level projections updated with two recent studies of the Antarctic contribution

3.3 Knowledge Gaps in Sayers et al. Projections

The projections by Sayers et al. are as comprehensive as can reasonably be expected, but omit several factors that may, or do, lead to systematic underestimates of total risk. These include:

- risks from coastal erosion
- changes due to storm surges (the original H++ scenario included a large increase for contingency planning; see also section 3.4)
- impacts of population increase on non-residential properties and infrastructure
- impacts of increased wealth or demographic changes on damages (likely higher) and protection levels (also higher, i.e. could be compensating)
- impacts on information and communications technology infrastructure, as it was not possible to assemble a national dataset
- Sites of Special Scientific Interest (SSSIs) and relative richness of biodiversity

- natural beach systems, when estimating the most vulnerable defences
- indirect damages from 'intangible' losses, such as physical and mental ill health.

In general, estimates of damages are very uncertain. One key uncertainty, which could lead to underestimation or overestimation of risk, is the indirect component of EAD (assumed to be 70 per cent of direct damages). Analysis of adaptation costs, i.e. a full cost-benefit analysis, was also beyond their scope.

Uncertainties (e.g. probability intervals) for the projections were not estimated. A full analysis would require cascading of uncertainties along the causal chain from sea level to impacts.

3.4 Other Knowledge Gaps

In the wider literature the following themes arise.

Storms – To what extent future changes in sea level extremes will be affected by changes in storminess or storm surges (as well as mean sea level) is not well understood, due to the challenges of statistical and numerical modelling of storms. While current projections indicate changes in storm surges will be small, this may be regionally variable and estimates are uncertain.

Coastal processes – Knowledge of coastal erosion is poor (e.g. Fitton et al. 2016), particularly coastal system interactions and feedbacks, and is needed for assessing risk of not only erosion but also coastal flooding. For example, there are knowledge gaps around the long-term availability of sediments borrowed to combat erosion on sandy beaches (Quante and Colijn 2016). The Dungeness nuclear plant incident was related to limitations of scale model physical testing of wave action on shingle (ONR 2014).

Infrastructure exposure and vulnerability – Poorly known aspects include exposures for oil and gas terminals and refineries (Dawson, R. et al. 2016), financial impacts of port disruptions (Adam et al. 2016), national ICT data (Sayers et al. 2015) and estimates of defence vulnerability.

Correlated risks – These are generally not well understood. Examples include flood events across large sections of coast or clustered in time (e.g. Haigh et al. 2016); risks of multiple types of flooding simultaneously, e.g. coastal and river; interdependencies of infrastructure systems and businesses; and dependencies of UK interests, such as energy infrastructure and business supply chains, on other nations more vulnerable to sea level rise (Dawson, R. et al. 2016).

Indirect and intangible losses – Many wider impacts of flood risk and events are difficult to measure and predict. For example, the indirect damages of the 2014 Dawlish line closure due to lost economic activity are unknown. Living on the coast has benefits for health and wellbeing, and coasts were identified as the habitat most valued by people. But the cultural, wellbeing and community impacts of flooding, such as effects on mental and physical ill health and community cohesion, are not easily quantified (Kovats and Osborn 2016).

Uncertainty quantification – There is a lack of formal quantification of uncertainties (i.e. statistical inference), which would allow robust comparisons of relative contributions to risk.

4. Response Options

In terms of global mitigation, the *Low–Medium* global mean sea level rise scenario approximately corresponds to meeting the targets of the United Nations Framework Convention on Climate Change (UNFCCC) Paris agreement, with global warming from preindustrial to 2081–2100 at the low end of the RCP2.6 and RCP4.5 projections (66 per cent or greater ranges 0.9–2.3 °C and 1.7–3.3 °C), the *High* scenario to missing the targets (RCP8.5: 3.2–5.4 °C), and the *Extreme* to missing the targets and high sensitivity of ice sheets to climate change.

The UK has world-leading science and engineering expertise in all aspects of sea level science and coastal flood risk assessment and management. This is an opportunity, as demand for these services is likely to increase (Surminski et al. 2016). The UKP09 projections will also be updated in autumn 2018 (UKCP18), which will include a new assessment of evidence for the *Extreme* (H++) scenario. A selection of response options is described below.

4.1 Improving Risk Assessment

To reduce flood risk uncertainty in general requires research, monitoring and regular re-evaluation of evidence, because the main drivers of sea level rise and exposure (changes in climate and population) cannot be controlled by national action (Kovats and Osborn 2016; Oppenheimer and Alley 2016). As one example of monitoring, Woodworth and Hibbert (2015) point out that if all British Overseas Territories had tide gauges it would contribute significantly to global monitoring as well as UK interests.

To reduce uncertainty and ambiguity in the Antarctic contribution to sea level rise requires assessment of sea level rise probabilities (Dawson, R. et al. 2016). This is challenging because models and assumptions vary substantially (Box 3; Hinkel et al. 2015): progress would be made by generating suites of projections using state-of-the-art models (e.g. Cornford et al. 2015) to compare with those from simpler models (e.g. Ritz et al. 2015), and by studying the potential for rapid ice loss by the ‘cliff failure’ mechanism proposed by DeConto and Pollard (2016). An online tool projecting sea level rise and impacts, revised annually with the latest data and understanding, would ensure risk managers have the best available evidence (see below).

To increase confidence that risks are not systematically underestimated requires improving data and understanding for storm surges, coastal processes, the impacts of population increase and demographic changes on risk, indirect impacts, infrastructure exposure and vulnerability, and correlated risks. For example, according to the CCRA: “There is an imperative to develop a national capability for performing infrastructure climate change risk assessments” (Dawson, R. et al. 2016).

4.2 Improving Risk Management

To substantively reduce flood risk (i.e. to implement *Enhanced Adaptation*) requires concerted action to reduce all three aspects: flooding, exposure and vulnerability. Reducing flooding has been found to be the most effective of the three, in part because land-use planning (reducing exposure) affects only new properties (Sayers et al.). One potential new opportunity identified by the Hendry Review is for the UK to become world leaders in tidal lagoons for energy generation, for which reducing flood risk can be designed as a co-benefit (Hendry 2016).

To estimate the net benefits of adaptation measures requires quantifying co-benefits and negative impacts. Co-benefits of adaptation include new opportunities for businesses, and improved health and wellbeing from green and blue spaces created by coastal realignment (Kovats and Osborn 2016). Negative impacts of adaptation include coastal erosion from loss of sediments caused by hard defences, and economic blight from flood risk planning.

To improve evidence-based risk management for infrastructure requires increased uptake of existing advice by businesses and individuals. Infrastructure with relatively low adaptation levels include the ICT sector (POST, 2015), and Network Rail and UK waste management (Dawson R. et al. 2016). The flexible TE2100 adaptation plan is widely cited as best practice that could be applied to other regions and sectors. Uptake could also be improved for business continuity plans, property-level protection measures and insurance.

To improve evidence-based risk management for communities also requires increased implementation of existing advice. The CCRA states there is evidence that local authorities in England have deprioritised climate change adaptation. For example, hazardous waste sites are not banned from being built in known flood risk zones (Dawson, R. et al. 2016), the current rate of managed realignment in England would need to increase five-fold to fulfil current Shoreline Management Plans (Kovats and Osborn 2016), and lack of early engagement with coastal communities is a current barrier to reducing risk (Kovats and Osborn 2016). Nicholls et al. (2013) discuss implementation and assess strengths and limitations of the SMP framework.

To increase the implementation of existing advice for communities requires improving datasets and their availability, as lack of local information can hamper adaptation efforts. Slow rates of managed realignment can be due to lack of cost-benefit analyses (Surminski et al. 2016), and planners have expressed frustration at the lack of spatial data to translate national guidance (Environmental Audit Committee 2015). One option would be to provide estimates by Sayers et al., such as the locations of the most vulnerable defences, to local authorities to update their SMPs. New whole-system modelling approaches to erosion, which represent interactions and feedbacks more fully and have been used for specific locations, could be applied across the UK to inform SMPs (e.g. Tyndall Coastal Simulator: Dawson et al. 2009; Nicholls et al. 2015; iCOASST project: Nicholls et al. 2016, and others in the same issue of *Geomorphology*).

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Technical Annex

The following are brief notes on additional analysis carried out for this evidence review: in particular, the interpretation of Sayers et al. scenarios in terms of global mean sea level rise, and the statistical interpretation of DeConto and Pollard (2016) in terms of probabilities. They are intended for technical documentation and future traceability, and can be ignored by the general reader.

Scenarios

Additional information for Box 2.

The UKCP09 projections for global mean sea level (GMSL) rise are taken from the IPCC Fourth Assessment in 2007, and are from 1980–1999 to 2090–2099 (Table 3.1 in Lowe et al. 2009). Projections are given below.

Scenario	**Quantile of GMSL projection (cm)**		
UKCP09 (SRES)	0.05	0.5	0.95
High (A1FI)	26	42.5	59
Medium (A1B)	21	34.5	48
Low (B1)	18	28	38

The scenarios of Sayers et al. for the CCRA are defined in terms of UKCP09 mean sea level rise for the UK, rather than GMSL, but the same principles are applied here to the global projections, so the scenarios can be compared with the latest literature on GMSL.

- The *2°C* scenario is the median (0.5 quantile) of the Low (B1) scenario, i.e. **28 cm** GMSL from 1980–1999 to 2090–2099.
- The *4°C* scenario is taken from:
    - the 0.95 quantile of the Medium scenario (48 cm), and
    - the 0.95 quantiles of the High scenario (59 cm), adding 17 cm/year over 105 years for dynamic changes not accounted for in the IPCC 2007 report (giving 77 cm), which are
    - interpolated using the corresponding projections of warming (2.8 °C and 6 °C from present day, respectively)
    - to give an estimated sea level for 4 °C warming, **59 cm** from 1980–1999 to 2090–2099.
- The H++ scenario is directly taken from the maximum of the H++ range in Lowe et al. (2009), **250 cm** from 1990–2100:
    - the use of the maximum value is confirmed by summing the rates in the Environment Agency report (2011) cited by Sayers et al. which gives 1.9 m by 2100, the maximum of the UK mean sea level rise range in H++ (Lowe et al., 2009).

The *Low–Medium*, *High* and *Extreme* sea level scenarios in this review therefore describe the Sayers et al. climate scenarios as 30 cm, 60 cm and 250 cm GMSL from 1990 to 2100 respectively.

According to the Climate Action Tracker website (retrieved 3 January 2017), the projected global mean temperature under current pledges is predicted to be 2.8 [2.3–3.5] °C by 2100 since preindustrial (median and 68% range). IPCC (2013) projected median and 66% or greater ranges for RCP2.6 and RCP4.5 are systematically lower: 1.6 [0.9–2.3] °C for RCP2.6 and 2.4 [1.7–3.3] °C for RCP4.5 (from Summary for Policy Makers Table SPM.2, adding 0.6°C for warming from preindustrial to present).

Return Periods

Additional information on return periods (section 2.1).

To convert an annual probability (p_{annual}) into a probability over *n* years:

$p_{new} = 1 - (1 - p_{annual})^n$

Note that this is only valid under current conditions: under sea level rise, for example, the probability would increase over a long period.

Current and Projected Impacts

Expected Annual Damages (EAD)

Additional information for national present day EAD (section 2.2) from Sayers et al. (2015, 2016).

- Total (direct and indirect): £538.5 million (of which direct property damages: £316.8 million – 58.8%)
    - England £443.2 m (82.3%), Scotland £43.9 m (8.2%), Wales £47.6 m (8.8%), NI £3.7 m (0.7%)
- Residential direct: £128.2 million (23.8%)
    - England £111.9 m (87.3%), Scotland £6.2 m (1.2%), Wales £9.8 m (7.6%), NI £0.3 m (0.2%)
- Non-residential direct: £188.6 million (35.0%)
    - England £148.8 m (78.9%), Scotland £19.7 m (10.4%), Wales £18.1 m (9.6%), NI £1.9 m (0.5%)

UK population proportions in mid-2015: England 84%, Scotland 8%, Wales 5%, NI 3%. (Source: Office of National Statistics, https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualmidyearpopulationestimates/latest, accessed January 2017).

Transport and Communications

Additional information for transport (section 2.2.1).

Sources for percentages of rail network currently at risk:

Total 16,512 km (Thornes et al. 2012) with 2537 railway stations (Dawson, R. et al. 2016), of which:

- 360 km railway length and 52 stations (Table 1) at significant risk: 2% and 2%
- 830km and 113 stations (Sayers et al.) at significant or moderate risk: 5% and 4%

Sources for percentage of UK strategic road network (motorways and trunk A-roads) currently at risk:

- Great Britain: 10,620 km (Thornes et al. 2012, cited in Dawson, R. et al. 2016)
- Northern Ireland: 1300 km (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/231647/1385.pdf, accessed 29 August 2017)
- UK total: 11,920 km
- Of this total:
    - 630 km (Table 1) at significant risk: 5%
    - 1830 km (Sayers et al.) at significant or moderate risk: 15%

Source for 1km roads at risk of erosion being for England only: Table 4.131 of HR Wallingford (2014) cited in Dawson, R. et al. (2016).

Sea Defences

Additional information on sea defences (section 2.2.1).

Sources for “England’s coastline is 4,500 km, of which nearly a quarter has coastal flood defences” and “Around 40 per cent of the English coast is liable to erosion, of which one-fifth is defended”:

Dawson, R. et al. (2016): 4,500 km total coast length in England; 1,800 km (40%) liable to erosion, of which 340 km (19%) is defended.

Sayers et al. (2015), Table 7-1: 114 km vulnerable length is 11% of total defended ~1036 km: rounded to 1100 km, i.e. 24% of coastline is defended.

Communities

Additional information on communities (section 2.2.3).

Fraction of population living near the coast:

- Updated URL for European Commission statistics (Eurostat) source: http://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Coastal_regions_-_population_statistics (accessed 29 August 2017)
- Table 2 – 36% and 63% population within 5 and 15km of the sea respectively.

Coastline definition:

- For Nomenclature of Territorial Units for Statistics (NUTS) regions, coastline is defined as Mean High Water mark
- Metadata URL: https://data.gov.uk/harvest/gemini-object/e8f7ffea-a7e7-4827-a819-ffcc83830914 (accessed 29 August 2017).

Sources of Uncertainty, and Knowledge Gaps

Antarctic Contribution to Sea Level Rise

Additional information for Box 3 and Figure 6.

A. Source for “Combining these gives a median of 67 cm by 2081–2100” and bounds of vertical dark blue bar in Figure 6:

IPCC (2013) – Chapter 13, Table 13.5 (Church et al. 2013). Total sea level rise for RCP8.5 from 1986–2005 to 2081–2100, median = 63 cm.

Antarctic dynamic contribution from 2000–2100, median = 8 cm (Gregory, 2015) (to use same date range as Ritz et al. 2015).

IPCC (2013) median sea level rise minus Antarctic dynamic = 55 cm.

Ritz et al. (2015) – Median and 5–95% range = 12 [2, 30] cm: Supplementary Material, Excel file in Ritz et al. Density estimates for blue shading from R data file also in Supplementary Material. Add to IPCC (2013) estimate of 55 cm.

IPCC (2013) with Ritz et al. (2015) median, 90% range (dark blue bar in Figure 6): 67 [57, 85] cm.

B. Source for “consistent with up to 5 per cent probability from Antarctica of sea level *fall* of 90 cm and also sea level *rise* of 230 cm”:

DeConto and Pollard (2016) – Subtract total Antarctic contribution from IPCC (2013), not dynamic only (Table 13.5: 4 cm from 1986–2005 to 2081–2100; 2000–2100 change not available) = 59 cm.

From DeConto and Pollard’s Supplementary Material:

- RCP8.5 results for 2000–2100, mean ± 1 std dev ($\mu \pm 1\sigma$):
- High Pliocene bound, with bias correction: 114 ± 36 cm
- Low Pliocene bound, no bias correction: 64 ± 49 cm.

Distributional assumption: cannot assume Gaussian or even unimodal distribution, as histogram of ensemble data is multi-modal (not shown), so assume only that it has finite variance. Chebyshev’s inequality (finite variance assumption):

$$\Pr(|X-\mu| \geq k\sigma) \leq \frac{1}{k^2}.$$

90% or greater range = [μ - kσ, μ + kσ], where *k* is derived from the above rather than the more common Gaussian interpretation. Setting Pr(..) = 0.1 to obtain 90% or greater probability interval, (and using equality, not inequality, from here on for simplicity in calculations):

$k^2 = 1 / 0.1$ by rearranging Chebyshev

k = sqrt(1 / 0.1)

= 3.16

Giving DeConto and Pollard (2016) 90% or greater ranges:

for High Pliocene, bias correction:

= [114 - (3.16 x 36), 114 + (3.16 x 36)]
= [0, 228] cm

and similarly for Low Pliocene, no bias correction:

= [-91, 219] cm

C. Source for bounds of grey vertical bars in Figure 6:

Add above ranges to IPCC (2013) estimate of 59 cm:

IPCC (2013) with DeConto and Pollard (2016) 90% or greater ranges (grey bars in Figure 6):

[-32, 278] cm for High Pliocene, bias correction
[59, 287] cm for Low Pliocene, no bias correction

D. Source for “allowing up to 18 per cent probability of exceeding [H++]”:

For probability of total sea level rise X exceeding 250 cm, use the Cantelli inequality:

$\Pr(X - \mu' >= k) = \sigma^2 / (\sigma^2 + k^2)$
where μ' = (59 + μ) cm

For high Pliocene, bias corrected (μ = 114 cm, σ = 36 cm):

k = (250 - 173) cm
= 77 cm
Pr(X - μ' >= *k*) <= 18%

For low Pliocene, no bias correction (μ = 64 cm, σ = 49 cm):

k = (250 - 123) cm
= 127 cm
Pr(X - μ' >= *k*) <= 13%

Probability of exceeding 250 cm: up to 13–18%
by interpreting DeConto and Pollard (2016) under the Cantelli inequality.

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