A Climate Change Report for Infrastructure

Working Technical Paper

Flood and Coastal Erosion Management

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Summary

Climate change has the potential to impact the performance of Flood and Coastal Erosion Management infrastructure (FCERMi) in a number of ways (see Summary table).To date these potential impacts have been dealt with in a rather rudimentary fashion through the consideration of precautionary allowances applied to the most basic descriptions of climate loads (i.e. sea level rise and changes in river flow). Little to no consideration is routinely given to changes in extreme values, storm sequencing and spatial coherence or the more subtle impacts of temperature, solar radiation and in-combination effects.

Summary table – a basic summary of issues

Primary load exposure	**Example infrastructure that may be influenced**	**Primary climate change sensitivity**		**Impact on FCERMi performance**	
		Change	Confidence	Scale of impact and examples	Confidence in impact
Pluvial	Urban drainage networks and above ground structures that may become saturated	Severity of individual storms	**Low**	**Moderate** Heightened run-off, increased flood flows	**High**
		Spatial coherence	**Low**		
		Temporal sequence	**Low**		
Fluvial	River embankments, culverts, barriers and pumps	Severity of individual storms (high flows and low flows)	**High**	**High** Crest overflow, by-passing, accelerated deterioration, reduced maintenance window, and an increase in the chance of failure.	**High**
		Spatial coherence	**Low**		
		Temporal sequence	**Low**		
Ground-water	Cliff slopes, foundations of raised structures, coastal wetlands	Mean and extreme values (higher and lower levels)	**Moderate**	**Low Moderate** Soil instabilities (slope failure) differential settlement (causing instability), greater/less saline intrusion.	**Moderate**
Coastal and estuarine	Hard and soft shoreline structures (seawalls, beaches to wetlands), tidal barriers	Higher mean sea levels (and associated increase in incident wave energy)	**High**	**Very High** An increase in the chance of failure due to, for example, increased overtopping, scour, beach lowering, coastal squeeze.	**High**
		Severity of individual storm	**Moderate**		

		(surges and waves)			
		Increased storminess (severity, frequency and sequence)	**Low**		
		Wave direction (mean)	**Low**		
		Salinity	**Low**		
		Acidity	**Low**		
Temp., solar radiation and drought	Earth embankments and other ‘soil’ and ‘vegetation’ based infrastructure	Extremes of temperature – cold and hot – and extreme dry periods	**High**	**Moderate** Accelerated desiccation of soils, freeze-thaw induced spalling, loss of strengthen in surface cover , loss of vegetation for green infrastructure , Surface drying and increased cliff erosion	**High**
	Catchment and local surface storage (e.g. SuDs)			**High** Changing nature of flora and fauna (see below)	**Moderate**
Problematic invasions and bacterial attacks	Potential to affect both hard and soft infrastructure in fluvial, coastal and estuarine settings	Changes in the prevalence and nature of microbes and invasive species	**Moderate**	**Moderate** Unwanted species (such as mosquitos around standing water and SUDs), Japanese knot-weed reducing channel conveyance, increased cases of accelerated low water corrosion in estuaries.	**Low**

The focus on precautionary allowances is perhaps one reason why limited progress towards the development of adaptive infrastructure has been made. There are few examples where infrastructure has been purposefully designed to facilitate future modification. Equally, the design and planning of flood infrastructure remains largely based on a ‘single’ design storm – a single coastal storm or rainfall event. The 2007 floods highlighted that a single spatially coherent event could affect large parts of the country simultaneously with severe knock-on impacts for supply chains and critical service provision. The 2013/14 winter floods further exposed this simple view as inadequate, highlighting the fundamental difference between a ‘single event’ and a ‘prolonged sequence of storm events’ with one storm after another falling upon an increasingly saturated land or attacking weakened structures (as witnessed in Dawlish). The importance of both the spatial coherence and temporal sequencing of storms events has been well known for some time but is not a standard consideration. Improvements in the richness of the climate projections (around extreme values, temporal correlations and coherence) will therefore need to go hand-in-hand with advances in the planning, design and management of FCERMi.

The scientific and practitioner community has also been slow to recognise the importance of *adaptive thinking*. Adaptation has traditionally been associated with organisations and the societies in general. This narrow view is not helpful in the context of FCERMi. Decisions concerning the design, construction and renovation of FCERMi are often equally long lasting and may be costly to reverse. Despite these challenges progress is being made but to move forward but significant innovations are required. Embedding a comprehensive consideration of climate change with FCERMi choices poses a significant challenge and will demand advances in:

(i) **Climate projections**– Information on climate has, to date, largely been focused on changes in mean values. The performance of FCERMi is fundamentally associated with changes in extreme values and more subtle climate characteristics such as spatial coherence and temporal sequencing. To progress our understanding of climate change impacts on FCERMi 'rich' climate projections will be needed.

(ii) **Scientific understanding infrastructure response to climate change** – Climate change can influence the performance of FCERMi in a number of ways, including the chance that:
   a. *The asset will be overwhelmed* - the nominal standard of protection afforded by the asset may decrease as linear structures (e.g. embankments) are more frequently overtopped and in-line structures are by-passed as flow rates exceed the capacity of the pump or culvert).
   b. *The asset will fail structurally*- due to an acceleration in the rate of deterioration or in response to more severe storm loads (or both)
   c. *The asset cannot be adequately maintained*- due to an increased frequency of on-demand use, a lack of down-time for maintenance may lead to an increase in on-demand failure (e.g. mechanical and electrical assets such as the Thames Barrier, fenland pumps, major gates etc).

(iii) **Improved appraisal methods –** Precautionary allowances have dominated the approach to FCERMi design in recent years. More progressive approaches that recognize and value the future as uncertain and encourage an appropriate, decision specific, degree of adaptive capacity within the design will need to be mainstreamed.

(iv) Innovation the planning, design and management of (natural and engineered) infrastructure - In part the limited adoption of more adaptive strategies within the FCERM industry is associated with difficulties in visualising exactly what these are and how they operate. Mainstreaming an understanding of adaptive options – with examples - will be needed to encourage innovative and development of FCERMi that is appropriately resilient to future change or capable of modification.

1 Introduction

Background

Living With Environmental Change (LWEC) have commissioned a series of Climate Change Report Cards to summarize the evidence on current and future impacts of climate change on infrastructure provision. It is envisaged that the information provided through the Report Card will be used to inform government policy, investment and LWEC's priorities for research and development. To date Report Cards have been produced on Water and Biodiversity (see http://www.lwec.org.uk/resources/report-cards).

The Infrastructure Report Card (IRC) will be based upon a series of Technical Papers that explore the impacts of climate change on a variety of UK infrastructure (Table 1). This report provides a supporting contribution to the UK Infrastructure Report Card on the topic of **"Flood and coastal erosion risk management infrastructure (FCERMi): Urban flooding, green infrastructure, water sensitive design, etc.''**

Table 1 Summary of contributions to the Infrastructure Report Card

#	Paper title
1	Transport: Rail
2	Transport: Road transport (including cycling and walking)
3	Transport: Air, Inland waterway, Port & Marine
4	Potable water: Water supply, treatment and distribution
5	Waste water and sanitation: Waste water collection, treatment and disposal (including consequences for the environment)
6	Flood and coastal erosion risk management: Urban flooding, green infrastructure, water sensitive design, etc
7	ICT: Service structures (e.g. masts, towers, and underground structures) and networks
8	Waste: Solid waste management – disposal, thermal processes, biological and mechanical processing, collection and other (e.g. construction, agricultural)
9	Energy: Nuclear, Coal, Oil & Gas - exploration, production, generation, sensitivity to water availability
10	Energy: Renewables generation
11	Energy: Power systems, transmission and distribution
12	Energy: Demand

Objectives

The UK Climate Change Risk Assessment (CCRA) provided the first comprehensive view of the potential impacts of climate change on a wide range of sectors across the UK and highlighted flood and coastal erosion as a priority area (Defra, 2012). The Flood and Coastal Erosion Sector Report that supported this conclusion also noted that with a significant legacy of flood and erosion defence structures, extending to over 40,000 km in length, adaptation is likely to present a major challenge (Ramsbottom *et al*., 2012).

The objective of this Report Card is to review current understanding of the impacts of climate change on FCERM infrastructure and the implications for planning, design and management of FCERM infrastructure across the UK including England, Wales, Scotland and Northern Ireland. Consideration of the risks in areas that these infrastructure protect is not the purpose of this Report Card.

Approach

This Report Card provides a synthesis of current and emerging knowledge. No new primary analysis is included. The approach to gathering the latest evidence has been through a literature review and dialogue with leading experts and a range of infrastructure managers (acknowledged at the start of this paper). Appropriate evidence from the CCRA Flood Report (Defra, 2012) is highlighted, but the CCRA focused on the analysis of risks in the floodplain, whereas this report focuses on the impact climate change may have on the infrastructure itself.

2. Scope

2.1 What is flood and coastal erosion risk management infrastructure?

The UK Government has a vision to provide *'An infrastructure network that is resilient to today's natural hazards and prepared for the future changing climate'* (HMGovernment, 2011). This report goes on to note that '*New infrastructure can be climate resilient by ensuring that an asset is located, designed, built and operated with the current and future climate in mind. Existing infrastructure can be climate resilient by ensuring that maintenance regimes incorporate resilience to the impacts of climate change over an asset's lifetime.* These goals equally apply to FCERM infrastructure (FCERMi) assets.

FCERMi includes any feature that is actively managed to reduce the chance of flooding or erosion (Sayers et al., 2010). The most common sources of flooding include:

- River flooding;
- Coastal flooding;
- Surface water flooding (including sewer flooding caused by rainfall overwhelming the sewers);
- Groundwater flooding; and,
- Reservoir flooding as a result of dam failure (not considered in this report).

The broad definition of FCERMi used here includes a wide variety of individual asset types (both local and system scale infrastructure assets) that act together to form diverse asset systems. As no comprehensive terminology exists to describe the domains of flood, coastal and surface water infrastructure a working ontology is presented in Table 2.

2.2 Definition of impact

Within this report the 'impact' of interest is associated with the influence climate change may have on the performance of FCERMi ('the pathways'), including the protection they provide, their reliability and condition. For example:

- Increasing the rate of material degradation (e.g. spalling of concrete, corrosion of steel, soil desiccation, surface cover erosion etc.)
- Increasing the rate of wear and tear of mechanical components (e.g. through increased 'on-demand' use)
- Increased severity of episodic erosion and damage to structural elements (e.g. removal of rock armouring, scour depths)

In response, the reliability of FCERMi may reduce, new designs and approaches maybe needed and maintenance budgets enhanced.

No effort is made in this report to determine the impact of infrastructure failure on the economy, society or ecosystems.

Table 2 An ontology of flood and coastal erosion infrastructure assets

Type of asset		Example activities
Local scale infrastructure		
Private homes and businesses	Avoidance	E.g. the use of planning to relocate new properties away from flood areas or above flood levels.
	Resistance	E.g. the use of flood products to prevent water entering a property.
	Recovery	E.g. the use of building materials and practice that aid the rapid return post internal flooding.
Critical service nodes	Avoidance	E.g. the use of planning to relocate individual sites away from flood areas or above flood levels; consider spatial coherence in the design of networks functions.
	Resistance	E.g. the deployment of property 'ring dykes'.
	Recovery	E.g. the use of function specific building designs and network redundancy to avoid loss of function if flooded (i.e. continued power or communication distribution).
System scale infrastructure		
Hard path infrastructure – Planning, design and management of built infrastructure		
Linear and network assets	Active	E.g. barriers that can be deployed as temporary and demountable defences.
	Passive - Above ground	E.g. raised defences and shore parallel structures (i.e. embankments, levee or dyke, breakwaters) through to storm water storage ponds.
	Passive - Below ground	E.g. individual pipes, CSO's and the drainage network they compose.
Point assets	Active	E.g. pumps, floodsgates and sluices.
	Passive	E.g. fixed trash screen, groynes as well as interface assets (that link above and below ground linear systems) such as manholes and gullies.
Soft path infrastructure – Utilizing natural infrastructure systems		
Watercourse	Channel	E.g. the management of vegetation (e.g. weed cutting) and sediment (e.g. shoal removal and dredging)
	Floodplain	E.g. the management of floodplain roughness and debris recruitment.
Coast	Foreshore and backshore	E.g. the management of dunes and beaches through active (e.g. recycling and profiling) and passive (e.g. sand fencing, marram grass planting) management as well as natural wetlands and soft cliffs.
Urban landscape	Urban land use	E.g. the engineering of urban green space, managing surface permeability (e.g. through SuDs) and debris recruitment.
Rural catchment	Rural land use	E.g. the management of rural run-off, sediment yields as and debris recruitment.

Note: Dams are excluded from this report

3 Scene setting

3.1 The role of FCERMi in managing risk

Flood waters for most of the UK are ‘controlled’ and most floodplains that contain significant economic assets are protected by some form of FCERMi. As such FCERMi provides a crucial risk management service to the UK economy (Table 3). Erosion is also a significant risk. Of the 4,500 km of coast in England, 1,800 km is liable to erosion (340 km of which is defended). In 2009 it was estimated that 200 properties were immediately vulnerable to erosion. By 2029 up to 2,000 residential properties and 15 km of major road and railway may become vulnerable (Halcrow, 2009). Although this report is focused on issues of flooding, erosion (particularly coastal risk) is closely linked with the performance of sea defences and hence flooding (link highlighted in the discussion present in Section 4.4.)

Table 3 Summary of flood risks in England, Wales and Scotland

	Source of flooding					Infrastructure assets at risk				
	River & coastal	**Surface**	**Total (River, coastal, surface)**	**Dam & reservoir failure**	**Expected annual damages**	**Water & sewage**	**Electricity**	**Railway**	**Main road**	**Police, Fire, Ambulance**
England	2.4m	3.8m	5.2m	1.1m	£1bn	55%	14% (~7000)	20%	10%	13% (~4800)
Wales	220,000	234,000	357,000		£200m	80%	22% (800)	33%	11%	19% (~790)
Scotland			125,000		£720-£850m					10% (fire only)
Northern Ireland	46,000	20,000		66,000	£291m					

Sources: Environment Agency, 2009a, b, c Environment Agency , 2011; SEPA, 2011; Rivers Agency, 2011, Ramsbottom et al, 2012.

More recently the Climate Change Risk Assessment (Flood and Erosion Sector Report, Ramsbottom *et al.,* 2012) notes: *‘The defence systems that protect the flood plains and coastline are well developed across most of the UK. There is likely to be a need to adapt the existing flood risk management systems for future change. The total length of flood defences is over 40,000 km, and adaptation is likely to present a major challenge.’*

The level of service provided by FCERMi fundamentally reflects two components: the standard of protection (primarily a function of geometry and local loading conditions) and their condition (primarily a function of construction material and structural integrity). Climate change has the potential to influence both of these components.

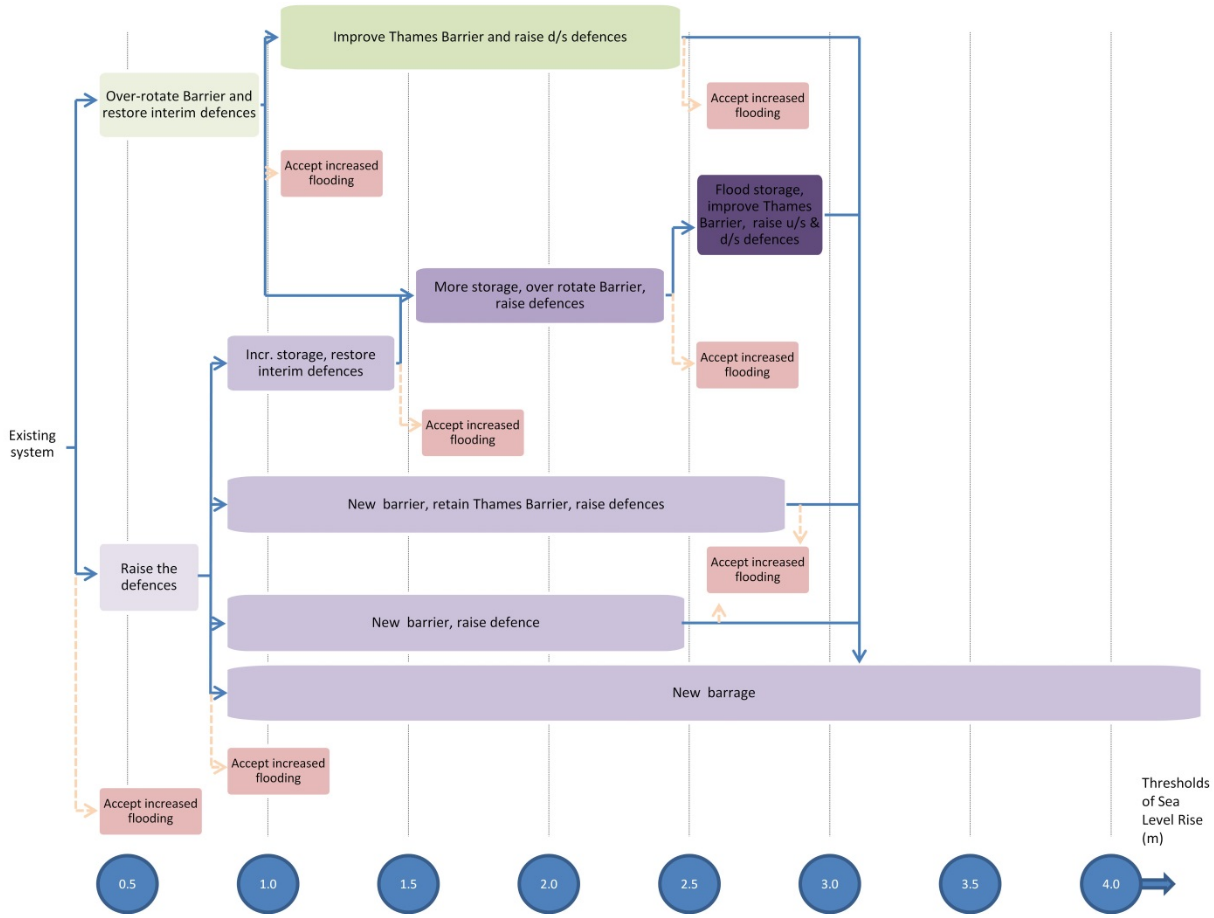
3.2Evidence of climate change as a priority for infrastructure providers

Seeking to establish a better understanding of climate change impacts and reflecting that in the planning of infrastructure investments is now recognised as an important activity by many of the major FCERMi infrastructure providers (including private, network rail etc, and public owners, Environment Agency, Local Authorities, Internal Drainage Boards etc). For many this is manifest within the planning processes only. For some the influence has extended to specific Strategy Plans. Overall, however, there remain few examples where infrastructure design has been changed.

Although the ownership of the FCERMi determines how the infrastructure is managed and adapted (or not), it does not alter the underlying climate change issues. To set this in context the approaches adopted by the three example infrastructure providers are discussed below before focusing on the more generic issues associated with the relationship between climate change and FCERMi in the remainder of this report.

Environment Agency

In the case of some major strategies the principles of adaptation are starting to influence practice. For example the Thames Estuary 2100 Strategy a set of plausible climate scenarios where used to underpin the development of possible adaptation pathways and the identification of a flexible strategy capable of coping with a wide range of alternative futures. The resulting strategy reassured government that the current defence system could cope with significant climate driven change if a programme of replacement and adaptation of existing infrastructure was followed and thus deferred major expenditure (see Figure 1 and a summary given in Tarrant & Sayers, 2012).



Source: (Environment Agency, 2009d)

Figure 1 The Thames Estuary Flood Risk Management Strategy incoporates options for future modification

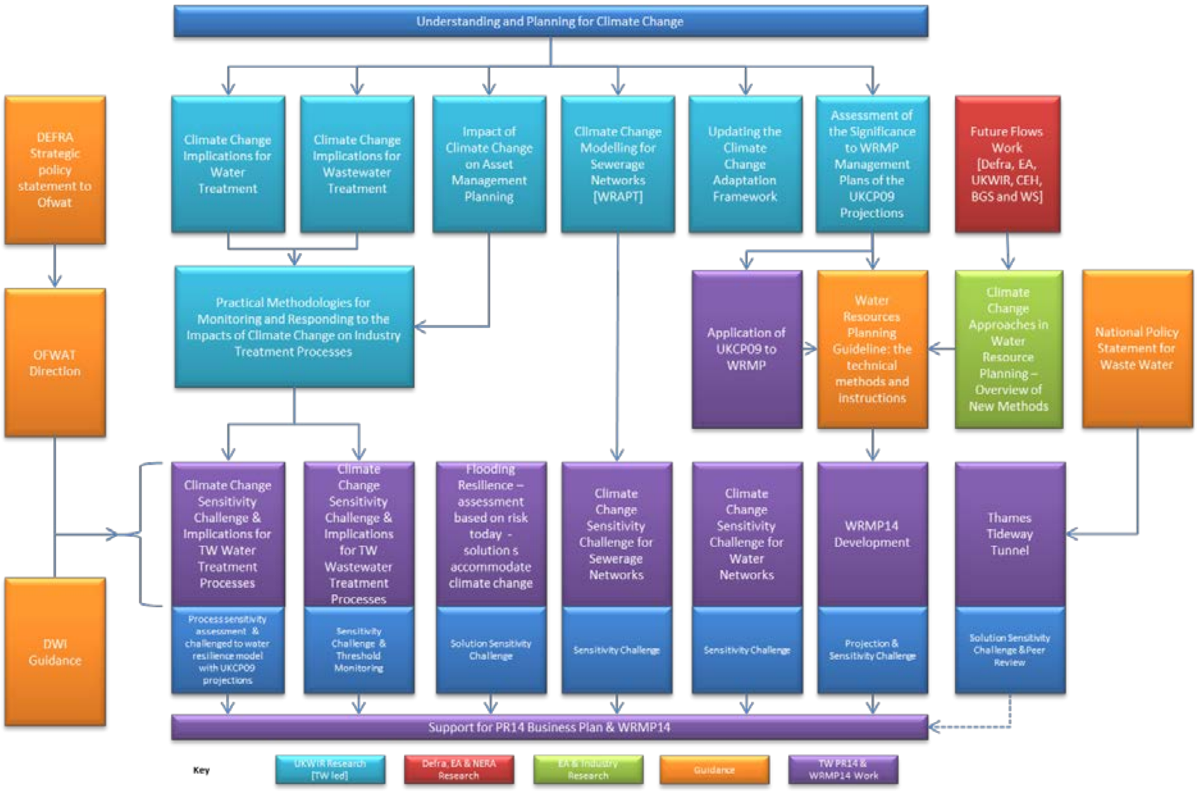
Thames Water

Customers are clear that they expect water companies to plan appropriately for the impacts of climate change and implications for delivery of the essential service. This is mirrored in guidance from Government and Regulators. Thames Water applies a variety of approaches:

- *Water Treatment Processes* - use of projections and sensitivity challenge and linked to 'business as usual' process monitoring performance;
- *Wastewater Treatment Processes* - sensitivity challenge, monitoring parameters identified. Decision support tool to allow monitoring analysis to be developed in Asset Management Programme 6 (AMP6);
- *Water Networks* – business needs for network improvement identified. Solution sensitivity challenged using possible climate futures derived from UK Climate Projections 09;
- *Wastewater Networks* – understanding the potential changes to rainfall intensity under future climate scenarios and applying to more sustainable, longer term solutions e.g. sustainable urban drainage schemes (SuDS) by working in partnership with other stakeholders to promote and deliver.

- *Flooding Resilience* – prioritisation of need based on current flooding risk with circa 7000 assets/sites assessed to have current flooding risk. Development of climate change resilient solutions to 2050s;
- *Water Resource Management Plan 14* - use of projections and sensitivity challenge. In line with Water Resources Management Plan guidelines but also explores the impact of Future Flows enhanced analysis on the robustness of the preferred plan;
- *Thames Tideway Tunnel* - solution sensitivity challenged using possible climate futures derived from UKCP09. Climate sensitivity challenge assessment independently peer reviewed.

This process is summarised in the figure below.



Source: from the Thames Water Climate Change Adaption Plan – provided courtesy Dr Keith Colquhoun

Figure 2 Understanding and Planning for Climate Change within Thames Water

National Grid

In order to address climate change issues service providers are taking stock of and updating their infrastructures to make them more resilient to extreme weather events. Climate adaptation studies of the energy networks have concluded that there is a need to upgrade existing design standards to safeguard the electricity grid against adverse temperature, precipitation, sea level rise and storm surge (ENA 2011, National Grid 2010). For example the guidelines for flood resilience of the electricity grid suggest incorporating design measures to protect against events with predicted return periods of 1 in 100 (river) or 1 in 200 (sea) for primary substations and 1 in 1000 year for grid supply points.

3.3 An overview from previous studies

Given sufficient information the performance of FCERMi can be represented using a fragility function that is derived from structural reliability analysis (Dawson & Hall, 2006; van Gelder *et al*., 2008, Sayers et al, 2012a). However, with incomplete nationally available data the impact of climate change on FCERMi in national studies has been assessed through changes in the Standards of Protection (SoP) that reflect altered loadings and assumptions about the accelerated rate of deterioration (see for example Foresight Future Flooding Studies (Sayers *et al*., 2007) as well as past national assessments (Halcrow, 2000; Hall *et al.*, 2003; Hall *et al.*, 2005; Halcrow, 2004; Environment Agency, 2009). In some cases the evidence used to assess the change in standard of protection has been well founded (e.g. Sutherland & Gouldby, 2003). The evidence on time-dependent deterioration processes and deterioration rates may change when exposed to more severe individual storms, changing patterns of storm sequences or clusters of events remains limited (e.g. Environment Agency, 2007; Buijs et al., 2009, Environment Agency, 2013).

In terms of design choices the Environment Agency's standing advice, in the form of 'change factors', are typically used (Environment Agency, Undated). Upper end, best and lower end estimates for changes in sea level rise, river flows and rainfall intensity are provided for the 2020s, 2050s and 2080s. The report also highlights a small number of modelled catchments where the potential change in river flows is significantly greater. For these changes a more extreme change factor (the so-called High ++ scenario) is used to give a much greater change in flow. In practice there is little evidence to suggest designers are fully exploiting the additional information provided by probabilistic climate outputs to influence their design choices.

4 FCERMi sensitivity to climate change

FCERMi respond to a combination of climate driven loads. It is not simply the most extreme events that are of interest, but the sequence storm events (including events that on their own may be considered moderate) and the combination of loads (temperature, waves, surge, etc.). Equally the adoption of risk based approaches to asset management investment means that events across a full range of exceedence probabilities (from frequently occurring to more extreme) are of interest (Sayers *et al.*, 2002, 2010, 2014). This chapter presents the climate driven loads and the potential changes in these loads that are of most interest.

4.1 Pluvial loading

Climate related variables of interest

- ***Intensity*** – Directly affects the ability of urban drainage and local land drainage systems to cope.
- ***Duration/sequences*** – Influences antecedent conditions, run-off and the moisture content of structures and green spaces.
- ***Spatial extent*** – Influences the effective design rainfall.

Evidence for change

The review of future flood risk (Wilby, 2012) presents the latest evidence in support of changes in extreme rainfall and studies to translate these to potential change in river flows. Overall the report concludes that '*pluvial studies generally report greater increases to multi-day precipitation totals, and proportionately greater changes to extreme single-day events'.*

Climate changes of most interest and their potential impact on FCERMi

Changes in mean values

Changes in mean rainfall and its influence on FCERMi has received little attention to date. Changes in variability and extreme values are considered to be more important – see the section below.

Associated tipping points

None

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Moderate**
- In the impact that a given change in climate will have on FCERMi: **High** (i.e. that sensitivity is low)

Changes in the severity of individual storms

Urban drainage systems (piped and surface storage services) and pumped catchments have a fixed capacity to accommodate pluvial events. Any increase in the severity of rainfall events and run-off will bring into the question the ability of these systems to cope.

Associated tipping points

Typically urban drainage systems operate to a standard of a 1 in 30 year return period or less. This is perhaps acceptable today, but in future conditions much more frequent flooding would cause significant disruption and impact water quality. The specific thresholds will however reflect the specific context of the system within which individual assets operate.

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Low**
- In the impact that a given change in climate will have on FCERMi: **High**.

Changes in spatial coherence and temporal sequencing (and persistence)

Drainage design over most of the past 150 years has focused on the design and construction of piped drainage and sewerage systems to collect and convey water from largely impermeable (sealed) surfaces. Although some consideration has been given to influence of permeable surface close to highways and other paved areas in shaping these designs, it has been assumed that large areas of urban and near urban green space simply drain by other means. This is often not the case and once such green space becomes saturated the resulting overland flow runs onto urban surfaces increasing pressure on urban drainage systems.

Associated tipping points

Without sufficient downtime to maintain M&E assets (such as major pumps, barriers etc.) reliability on-demand is likely to decrease (Atkins, 2006). Determining what is 'sufficient' will be asset specific and difficult to generalise. The threshold for this is determined by the extent of sea level rise. At their most extreme, areas that currently drain naturally may become tide-locked and require constant management of river and urban drainage water flows.

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Low**
- In the impact that a given change in climate will have on FCERMi: **High**.

Summary implications for FCERMi

Pluvial loads are of primary concern in assessing the performance of urban drainage infrastructure. Drainage systems can become overloaded when (i) the rainfall intensity exceeds the design standard or (ii) when less intense, long duration rainfall saturates the ground increasing the effective impermeable area (Dunne and Black, 1970). The former tends to be caused by convectional rainfall (thunderstorms), often, but not always, with short duration and relatively low depth, and the latter is caused by long duration, perhaps stalled (stationary) cyclonic (frontal) rainfall with relatively low intensities but high depth because of the long duration. For the same depth of rainfall, the latter occurs more frequently than the former. This means that flooding is more likely to be caused by runoff from saturated green space than it is to be caused by intense rainfall. The high rates of surface run-off can also heighten debris recruitment (leaves, wood and the anthropogenic debris), subsequent transport and blockage (Streftaris et al., 2012).

Increased precipitation causing higher moisture contents of earthen embankments, leading to reduced soil suction (on which the stability of many of our over steepened embankments rely) increasing pore pressures and increasing likelihood of mass instability.

4.2 Fluvial loading

Climate related variables of interest

- ***High river flows*** and water levels are of primary concern in assessing the performance fluvial infrastructure such as embankments and barriers. High river flows can scour the toe of an embankment or bridge and lead to collapse (Cardoso and Bettess, 1999; Sturm et al., 2011). In-river water levels, either above and below the crest level of embankment, can drive a chain of processes that can lead to collapse and breach. High river flows can also recruit and transport debris leading to blockage of point assets such as culvert entrances and bridges (Schmocker and Hager, 2013; Wallerstein et al., 2013).

- ***Low river flows*** are typically not associated with the catastrophic failures that can result from high flows, but when coupled with warmer temperatures can lead to drying out of embankments and other weathering related deterioration (Sentenac et al., 2013).

- ***Storms sequences and clusters -*** Floods are often not driven by individual extreme events, but they can be the outcome of a cluster of events. The nature and sequencing of the events in each cluster is an important (Kilsby *et al.*, 2007) determinant of the associated flood risk. Similarly, the frequency and duration of intermittent dry periods also impacts flood defence infrastructure as noted in Table 3. Changes in the intermittency and clustering of extreme events are anticipated by some studies, but remain uncertain (Chun *et al.*, 2013; Whal *et al.*, 2013).

  The flood events through 2013/14 appear to have highlighted that there is still insufficient knowledge about the subject of the resistance of grass covered slopes to repeat exposure to storms (to be confirmed as the forensic analysis of the 2013/4 events are reported). Perhaps, however, the winter floods have highlighted that some of the biggest uncertainties lie in our understanding of the existing climate (especially in the area of storm sequencing) even before forward-projections of climate change are made. These sequences may well be critical and may require re-evaluation of the statistical loading paradigm under which infrastructure is currently evaluated.

Evidence for change

A recent review of future fluvial changes (Wilby, 2012) concludes that *'fluvial studies show mixed results* (with some regions likely to see an increase in flows and others a decrease) *as a consequence of complex interactions between regional climate change signatures and local variations in catchment properties.'*

Changes of most interest and their potential impact on FCERMi

Changes in mean values

Changes in mean fluvial flow and its influence on FCERMi have received little attention to date. Changes in variability and extreme values are considered to be more important (see the section below).

Associated tipping points

None

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Moderate**
- In the impact that a given change in climate will have on FCERMi: **Moderate** (i.e. that sensitivity is low)

Changes in the severity of individual storms

The morphology of the catchment may be significantly shaped by the individual storm events (Table 4). Increased erosion (including scour around bridges, embankments, bends etc.) and associated accretion (leading to loss of channel section or blockage) can undermine the performance of FCERMi. Severe scour can quickly lead to collapse (as witnessed for example in the bridge collapse at Workington in 2009 just upstream from Cockermouth).

Table 4 Potential effects of changes in fluvial flows on infrastructure

Effects of river flow changes on assets can include …	***Leading to…***
Changes to hydraulic gradients producing different wetting /drying…	…changes to internal strength /stability with the following related impacts: piping, cracking, fissuring
Increased velocities producing increased abrasion/impact damage and toe scour…	…changes to external strength /stability with the following related impacts: damage to armour protection and point structures, deterioration of wall material, toe scour leading to undermining / sliding /rotation
Increase in over-washing under extreme events …	…changes to external/internal strength/stability with the following related impacts: damage to slopes/crest and increased backfill washout

Source: (Environment Agency, 2014)

Associated tipping points

Within fluvial and urban drainage infrastructure various tipping points exist. Although the specific thresholds will reflect the specific context of the system within which individual assets operate, some of the potential issues are discussed below.

- **Moving gated weirs** (Environment Agency, 2014) – Moving gates (such as radial and buck gate weirs) are normally designed so that the underside of the gate(s) can be raised above an anticipated peak water level. A 30% increase in peak river flows could result in water levels that will either remain within bank top level, or flow out of banks and possibly by-pass the weir. Increasing the level to which the gate(s) may be raised may not be practical without considerable alterations to gate lifting machinery and walkway/operating platform, and may not be sufficient by itself to prevent flows by-passing the weir.
- **Fixed Crest Weirs** – In most cases it would not be feasible to lower crest levels to accommodate increased flows without lowering the normal upstream retention level. Improving the capacity of these structures is likely to require costly modifications (e.g.

extension or replacement by moving gates with sill levels lower than the fixed crest level).

- **Locks and other navigation control structures** - In most cases there is little risk to the structural integrity of a lock or a code compliant design for boat lay-bys / landing stages. In some Anglian Rivers such structures are used for flood flow transfer and could require modification to accommodate increased flows.
- **Morphological responses** – As river systems attempt to adjust to the changing climate, but are constrained by fixed defences, scour is likely to result. Maintaining a stable morphological channel artificially is a difficult (and costly) tasks and is likely to be unsustainable in some instances.

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Low**
- In the impact that a given change in climate will have on FCERMi: **High** (i.e. that sensitivity is high)

Changes in spatial coherence and temporal sequencing (and persistence)

Changes spatial coherence and temporal sequencing on different aspects of FCERMi include:

- ***Passive structures*** – the 2013/14 floods have highlight the potential damage to fluvial structures that prolonged exposure to fluvial loads can cause. Sustained scour of bridge piers and embankment foundations as well as persistently saturated soils have been highlighted as important concerns. Although evidence is limited within the climate projects persistent and prolonged events will pose significant threats to the performance of infrastructure.
- ***On-demand assets (pumps and barriers etc.)*** – The 2013/14 floods have highlighted inadequacies of many pumped drainage systems to cope with prolonged intense rainfall (as witnessed across the Somerset Levels for example). Increased frequency of 'on-demand' use will restrict the window for significant maintenance and repair with potential impacts on reliability of performance, an issue that is a key consideration for the Thames Barrier (Harvey et al., 2012).

Associated tipping points

Without sufficient downtime to maintain M&E assets (such as major pumps, barriers etc.) reliability on-demand is likely to decrease (Atkins, 2006). Determining what is 'sufficient' will be asset specific and difficult to generalise. The threshold for this is determined by the extent of sea level rise. At their most extreme, areas that currently drain naturally may become tide-locked and require constant management of river and urban drainage water flows.

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Low**
- In the impact that a given change in climate will have on FCERMi: **High** (i.e. that sensitivity is high)

Summary implications for FCERMi

The Environment Agency (2014) report explores the impact of climate change on fluvial assets through a qualitative review of design criteria. The study considered a range of asset types and how they might be affected by an increase in fluvial flows. The conclusions of are summarized below.

Moving gated weirs and fixed crest weirs

It may become necessary to increase weir capacity – this could include weir enlargement and raising of bank level in the vicinity of the weir. Enlargement could be by extension, through adding gate(s), and/or by lowering the sill level, if practicable, and providing new deeper gates to ensure the required retention level is retained. For both moving gated and fixed crest weirs, increased flows increase the risk of low passage around the side of the structure; depending upon the nature of the ground material, the extent of wing wall return in to the banks, and the presence and type of any bank protection adjacent to the structure.

Scour protection on the channel bed downstream of the structure may well be in the form of stone blocks and/or concrete bags placed on to the channel bed, and designed for current attack. Increased flows could increase results in the velocity exceeding the design velocity of the protection, there could be a significant effect upon the stability of the protection.

Vertical sheet piled bank protection

For both cantilever and tied back systems, increase bed scour (that may result from increased flows) may increase active forces, reduce passive forces and increase loads in anchorages. Increase scour will use up the scour allowance and safety factors included in the calculations. The severity of the impact will depend upon: the location of the defence; the nature of the bed material and its scour resistance; and the presence or absence of toe protection, such as rock-fill. Outer bends of rivers and banks in the path or weir streams will be the most vulnerable. Weak soils at the ends of pile lines will be vulnerable to increased flows/erosion, leading to wash out behind pile lines.

Vertical/gravitywalls (concrete, brick and masonry)

Increased flow velocities will increase erosion of the bed on passive side; initially reducing the erosion allowances made in the design. Further erosion could eventually lead to failure by sliding and/or rotation. The severity of the impact will reflect the nature of the design, for example the presence or not of a shear key (to prevent sliding); the resistance of the soil on the passive side to scour; and the presence or absence of toe protection such as rockfill; gabion mattress; or toe piling.

If properly designed, a 30%increaseinpeakflow is unlikely to have a significant impact on existing gravity structures.

Timber structures

Timber structures tend to have a limited penetration into the bed and hence may be susceptible to relatively small increases in scour (undermining of timber boarding) and washout behind at the ends of structure (outflanking).

Gabion walls

Increaseflowscanmakegabionsmorevulnerabletoerosiondamagebyabrasion.Wellpackedgabionswithprotectedmeshandadequatepenetrationbelowbedlevelareprobablynotathighriskfromincreased flows. Poorly designed or inappropriately located gabions however maybe vulnerable.

Sloping embankments and walls

Generally, increased flows will increase tendency to cause damage to or wash out fine materials from the under-layer of permeable revetments; and to increase drag forces on to the armour layer of permeable and impermeable revetments. The nature of the toe protection and revetment cover material will determine the specific impact that climate change may have.

Culverts and trash screens

The effect of 30% flow increase upon a culvert depends upon existing working capacity of the culvert and upon the capacity of the channels upstream and downstream. Increased flow velocity could help to flush sediment from the invert. If the culvert is working at full available capacity, increase inflows would increase headwater levels upstream of the culvert with increased probability of flow exceeding the existing bank full level. Increased flows may also mobilise additional material that could cause blockage.

4.3 Groundwater loading

Climate related variables of interest

- ***Higher groundwater flows and levels -*** Although few infrastructure have the sole purpose of managing groundwater floods, groundwater flows are an important consideration in understanding the performance of raised defences. For example groundwater flow can (i) bypass a raised defence and flood the land behind (Macdonald et al., 2012); (ii) exacerbate scour (Loveless, et al., 1996), (iii) drive progressive erosion and piping of the embankment or foundation soils (Schweckendiek et al., 2014), and (iv) destabilize soil slopes and cliffs increasing the chance of a catastrophic slip (Iverson & Major, 1986). Recent discussions have also focused on the relationship between increased groundwater levels and ingress in to the piped drainage system via below ground pathways (but limited evidence exists).

- ***Lower groundwater flows and levels -*** During extended periods of lower than average rainfall groundwater levels can fall leading to differential settlement and resulting instability (Wols and van Thienen, 2014), with significant impacts on urban infrastructure, including FCERMi assets (Foster, 2001). Lower groundwater levels at the coast can also lead to extended saline intrusion; exacerbating the corrosion of engineered infrastructure and the impacting the natural infrastructure capital of coastal freshwater water and brackish lagoons (Hiscock, 2011).

Evidence of change

Jackson et al. (2013) reviewed ten separate studies, covering 12 sites, which projected potential groundwater recharge rates in the UK over the 21st century. The findings highlight a consensus in the changes to mean annual potential recharge, with most studies simulating a decrease by the 2050s (although projections are in the range ~ -30% – +21%). There is most agreement for Chalk catchments in southern England, where the length of the recharge season is likely to shorten. However, Taylor et al. (2013) highlight a limited understanding of the interaction between groundwater and climate processes.

Changes of most interest and their potential impact on FCERMi

Changes in mean values

Changes in mean groundwater levels can exacerbate all of the design and performance issues driven by groundwater. Increased groundwater levels, higher than design levels can cause soil instabilities and prevent free draining of the waters that overtop or overflow a defence. Lower than design groundwater levels can lead to differential settlement causing instability. More specifically:

Increased mean levels - can drive (i) greater head under/through raised flood defence assets, increasing the chance of mass movement or piping, (ii) destabilise soft cliff slopes (such as Lyme Regis, Scarborough and elsewhere) increasing the need for cliff drainage and stabilisation, and (iii) lower the threshold for liquefaction. Increased mean levels can increase the frequency of “sunny day flooding”, placing additional strain on pumped drainage systems and potentially making them untenable (Strowd, 2013).

Decreased mean levels – can drive (i) soil shrinkage, settlement or subsidence (lowering crest levels and reducing standards etc.) and (ii) (together with sea level rise) promote saline intrusion in coastal margins, that may in addition to impacting species and the vegetation, expose flood defence assets to a more corrosive environment that anticipated.

Associated tipping points
None

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Moderate**
- In the impact that a given change in climate will have on FCERMi: **Low** (i.e. that sensitivity is moderate)

Changes in extreme values

Changes in extreme groundwater levels can, as changes in mean values, exacerbate all of the design and performance issues driven by groundwater (see above). Extreme values of groundwater tend to be slow to respond to driving rainfall conditions, therefore the temporal sequencing and spatial coherence of rainfall events are important.

Summary implications for FCERMi

Beyond the general points introduced above specific implications or requirements for modifications remain difficult to identify.

4.4 Coastal and estuarine loading

Climate related variables of interest

The wave climate (and the characteristics and sequencing of the individual storms within it), surge and mean sea levels are all important considerations at the coast. The wave climate typically drives the morphological response of the coastal system (the evolution of beaches, dunes and spits etc.) whereas the severity of individual or groups (both correlated sequences and correlated clusters) of storms determines the short to medium term performance.

Some of the most important variables are elaborated below:

- ***Tidal level*** - The tidal level (made up of a combination of astronomical and surge conditions) is a key control on the tidal window and periods of exposure and, due to the depth limited nature of much of the UK coast, the size of the waves reaching the shoreline. In extreme cases tidal levels may exceed crest levels. The resulting overflow can lead rapidly to breach of raised assets such as coastal embankments, dunes, barrier beaches and shingle ridges (Wadey, et al., 2012).

  A quantified exploration of the potential impacts of climate change at the coast was presented in the Defra commissioned study in Coastal Defence Vulnerability 2075 (CDV2075, (Sutherland & Wolf, 2001; Sutherland & Gouldby, 2003). This study considered a range of climate drivers and highlighted:

- *Increased overtopping* - Sea level rise of 0.35 m will cause average increases in overtopping volume of between 50% and 150%, depending on structure type, location and modelling approach, assuming present day defences are unchanged in 2075.

- *Increased scour potential* - Scour and structural damage potential may increase by 16% for the vertical seawall and less than 2% for the sloping embankments and shingle beaches. Although there was lower confidence in this statement as it will depending on how the partial standing wave velocities at a specific coastal structure change.

- *Accelerated coastal steepening* - If the observed coastal steepening (Soulsby et al., 1999) continues in response to sea level rise, overtopping rates will increase by a further 15%, approximately.

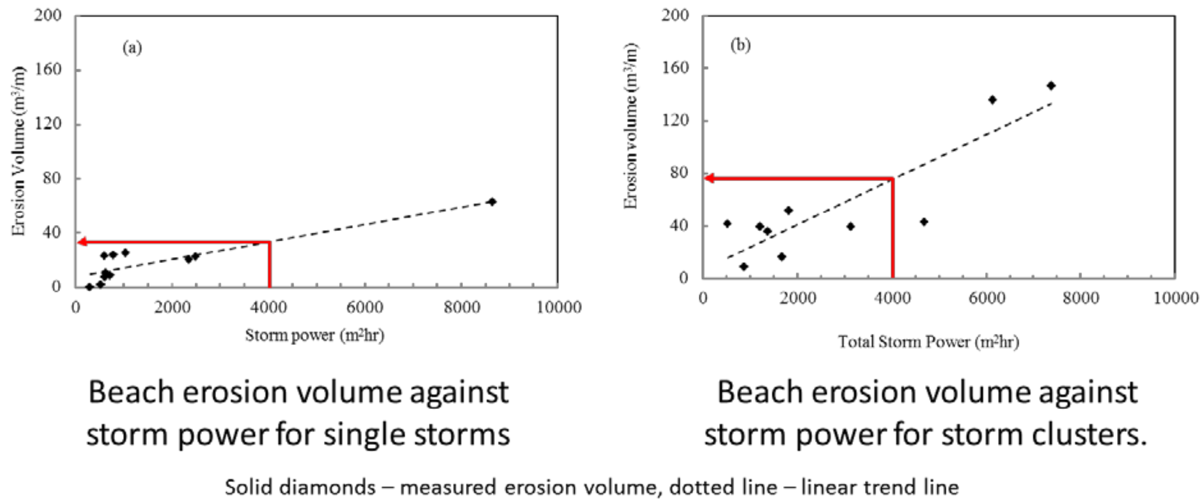
Although each stretch of coastline will respond differently CDV2075 concluded that the standard of protection provided by coastal structures was most sensitive to sea level rise (see Appendix 1). Dawson et al. (2009) demonstrated that long term changes in flood and erosion risk in North Norfolk were also significantly more sensitive to sea level rise than changes in growth of offshore wave heights and changes in direction.

Other possible influences include loss of saltmarsh buffers; saline intrusion; beach lowering and liquefaction (Sutherland et al., 2007); tidal locking of drained catchments as well as the creation of some opportunities, for example to create wetlands.

The operations of tidal barriers may also be affected. The recent Thames Estuary 2100 studies (Environment Agency, 2009d) confirmed that The Thames Barrier is likely to provide an adequate standard of protection to 2070 (although this is to be reviewed as the reality of sea level rise becomes known). However, operational constraints, in particular the pressure increased closure rates may place on maintenance regimes could be a significant issue. The increased frequency of on-demand use will be a significant challenge for all FCERMi as climate changes.

- ***Joint waves and surge*** - The incident wave angle, height and period and the coincident tidal conditions all influence impact pressures, overtopping rates (Pullen et al., 2007) and sediment transport rates along and cross shore (Chini et al., 2011). Toe scour is typically more responsive to incident wave height and period alone (Environment Agency, 2012).

- ***Storm sequencing***- Beaches undergo continuous and on-going morphodynamic changes as a result of waves, tides and wind at a range of time scales. Significant erosion however is typically episodic (as exemplified by the 2013/14 event) and takes place in response to a combination of the wave conditions, water levels, groundwater as well as geology and presence or absence of structures (local or remote to the site). Impacts of individual storms and the impact of clusters of storms, where storms occur at close succession, are both extensively discussed in various papers (an example from the FloodMemory project is given below).



Source: (Karunarathna, et al., 2014)

Figure 3 The effect of storm clusters on a Narrabeen Beach Australia

Evidence of change

Sea level rise (Horsburgh and Lowe, 2010) **-** Global sea level has risen at a mean rate of 1.8 mm per year since 1955. From 1992 onwards a higher mean rate of 3 mm per year has been observed. Sea-level rise measured over the UK is consistent with the observed global mean. Looking to the future projections of change in the UK suggest a rise of between 120 and 760 mm by 2095, compared to a 1980-1999 baseline. This approximately equates to rates of between 1.2 and 7.6 mm per year respectively. Considering projected land movements, a greater rise in southern regions of the UK is likely relative to the north.

Storm waves and surge (Woolf and Wolf, 2010)
There is no consensus on the future storm and wave climate for north-western Europe (largely due to variation in projected future storm tracks amongst atmospheric models. The UKCP09 wave model show storm tracks moving south, and this may result in lower wave heights to the north of the UK and slightly larger wave heights in some southern regions, especially the south-west (but a **low confidence** is assigned to this finding).Using an ensemble of climate model runs Hemer et al. (2013) estimate a projected increase in annual mean significant wave heights of 7.1% over the global ocean. There is little evidence on how climate change might alter (if at all) the correlations between waves and surge levels.

Storm sequence (uncorrelated) and clustering (correlated)- The devastating impact on asset performance of prolonged sequences of storms has been well demonstrated during the 2013/14 event (such as at Dawlish). There is however little accepted research on how storm sequences will change in the future. Despite the limited evidence for future change, this is an area rightfully attracting more attention as it has been a missing consideration in traditional design considerations.

Dominant wind direction - This is a variable that could impact beach sediment movement and the performance of backshore structures as well as beach control structures. There is however little evidence that provides a clear indication of change and, in most cases, local refraction and diffraction processes are likely to reduce the impact of a change in the offshore climate by the time the waves reach the shoreline.

Salinity (Holiday et al, 2010) - There is no consensus as to the future changes in the salinity of shelf seas and oceanic surface waters, although a low confidence that it decrease slightly. Given this and relatively weak link between small changes in salinity and infrastructure performance (other than the viability of wetlands and other soft path infrastructure), changes in salinity are not discussed further here.

Ocean acidity (Turley et al., 2010) - There is a high confidence that the ocean is becoming more acidic as increasing amounts of atmospheric carbon dioxide (CO_2) are absorbed at the sea surface. Models and measurements suggest about a 30% decrease in surface pH (an increase in acidity) and a 16% decrease in carbonate ion concentrations since 1750.The rate of change in pH is faster than anything experienced in the last 55 million years and is causing concern for marine ecosystems and species. There is also a high confidence that oceans will continue to acidify with increasing CO_2 emissions. The performance of natural infrastructure systems, coastal wetlands in particular, may be influenced by these changes.

Changes of most interest and their potential impact on FCERMi

Changes in mean sea levels

An increase in mean sea level (driven by sea level rise) is of fundamental important in determining the future performance of coastal infrastructure. This is for a number of reasons:

- **Depth limited nature of the present day waves** - The majority of the UK's sea defence structures have depth-limited design wave conditions, which implies that the largest nearshore waves will not necessarily increase if offshore waves do (Burgess & Townend, 2004). However, coincident mean sea level rise will reduce the depth-limiting effect of nearshore waves. In turn this leads to increased overtopping and the severity of wave impacts (and subsequent structural damage and increased breach potential). It should be noted, however, that larger waves are likely to drive coastal morphology change at a greater rate than sea level rise, so over the medium to long term any growth in offshore wave heights may well be expressed at the coast (Hall, et al., 2006).

- **The construction of fixed shorelines** – Unconstrained, beaches are naturally resilient to progressive slow change, changing shape and extent naturally in response to storms and variations in sea levels, wave climate and currents. Significant lengths of coast are however protected by engineering structures (46% of England's coastline; 28% Wales'; 20% Northern Ireland's and 7% of Scotland's is protected by artificial structures, LWEC Report Card). Many of these structures fixed the location of the backshore and prevent natural onshore migration. As a result, beaches and wetlands can be trapped in a 'coastal squeeze' between rising sea levels and the fixed shoreline.

Table 5 Potential effects of sea level rise on coastal infrastructure

Effects of sea level rise on assets can include	*Leading to …*
changes to hydraulic gradients lead to different wetting / drying …	… changes to internal strength / stability with the following related impacts: piping, cracking, fissuring
increased velocities lead to increased abrasion / impact damage and increased toe scour …	… changes to external strength / stability with the following related impacts: damage to armour protection, deterioration of wall material, toe scour leading to undermining / sliding / rotation
increase in overtopping under extreme events …	… changes to external / internal strength / stability with the following related impacts: damage to crest / increased backfill washout
increase in loading on structure from larger waves and deeper water levels …	… changes in external strength / stability with the following related impacts: damage to armour protection, deterioration of wall material, structural instability leading to sliding

Source: (Environment Agency, 2014)

Associated tipping points

Much of coastal defence systems operate in a state of dynamic equilibrium. When such infrastructure is lost (or withdrawn) the coastal rebound can be significant as rapidly adjusts to a retreat position in an attempt to establish a natural equilibrium state with the surrounding coast (e.g. as seen in Happisburgh). Significant feedbacks therefore exist if this is lost: beach lowers, depths increase, depth limiting reducing and beach lowers further.

Across much of UK schemes are designed to specific standards of overtopping to provide the safety of promenade users and/or the structural stability of the crest and backshore cover. These thresholds are very sensitive to small changes in sea level as highlighted by the rapid raise in failure probability as overtopping rate near critical values these values (Environment Agency, 2007).

Although tipping points are site specific sea level rise is likely to have the must acute impact on the defence systems (the impact wave energy and their standard of protection) where the waves are depth limited and the extreme water levels change only marginally with increasing return period (Sutherland et al, 2001 and Haigh et al 2010) . When they are exceeded however this may drive the need to move from one form of infrastructure to another. For example, the ability of a beach and dune systems to adapt to sea level rise may be limited by the availability of space to retreat and the supply of sediment. As a result, at some point alternative systems of defence may be needed. Equally, estuary barriers may need to be replaced by barrages, and indeed estuaries currently without barriers they may become the only viable means of protection 9as it becomes impractical to raise linear defences further).

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **High**
- In the impact that a given change in climate will have on FCERMi: **High**.

Changes in dominant wave direction and associated steepness

The dominant wave direction is a central driver in determining longshore drift and, in combination with other coastal factors, morphology change (Chini and Stansby, 2012). Changes in wave steepness, associated with larger waves arriving at the coast because of sea level rise, can alter their beach building/beach eroding characteristics. Both of these changes can influence the performance of natural beaches and beach nourishment schemes (Hinkel *et al*., 2013; Hall *et al.,* 2014).

Table 6 Potential effects of changes in wave climate and surge on coastal infrastructure

Effects of wave climate changes on assets can include …	*Leading to …*
increased velocities lead to increased abrasion / impact damage and toe scour …	… changes to external strength / stability with the following related impacts: damage to armour protection, deterioration of wall material, toe scour leading to undermining / sliding / rotation

increase in overtopping under extreme events …	… changes to external / internal strength / stability with the following related impacts: damage to crest / increased backfill
increases in loading on structure from larger waves and deeper water levels …	… changes in external strength / stability with the following related impacts: damage to armour protection, deterioration of wall material, structural instability leading to sliding

Source: (Environment Agency, 2014)

Associated tipping points

None

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Low**
- In the impact that a given change in climate will have on FCERMi: **Moderate**

Changing the severity of individual storms

The severity of individual storms is likely to increase in response to sea level rise (see above). Overtopping is likely to increase and so too the potential for breach. Increased incident waves heights may also increase the change of momentary liquefaction and potentially destabilize coastal structures.

Associated tipping points

Without sufficient downtime to maintain M&E assets (such as major pumps, barriers etc.) reliability on-demand is likely to decrease. Determining what is 'sufficient' will be asset specific and difficult to generalise.

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **High** (given depth limited nature of much of the UK coast)
- In our assessment of FCERMi sensitive to this change: **High**.

Changes in spatial coherence and temporal sequencing (and persistence)

Although well recognized as an important climate variable to be more centrally considered in the design and management of FCERMi evidence on the change spatial coherence and temporal sequence remains limited and is set to be an area of increased research focus in coming years.

Associated tipping points

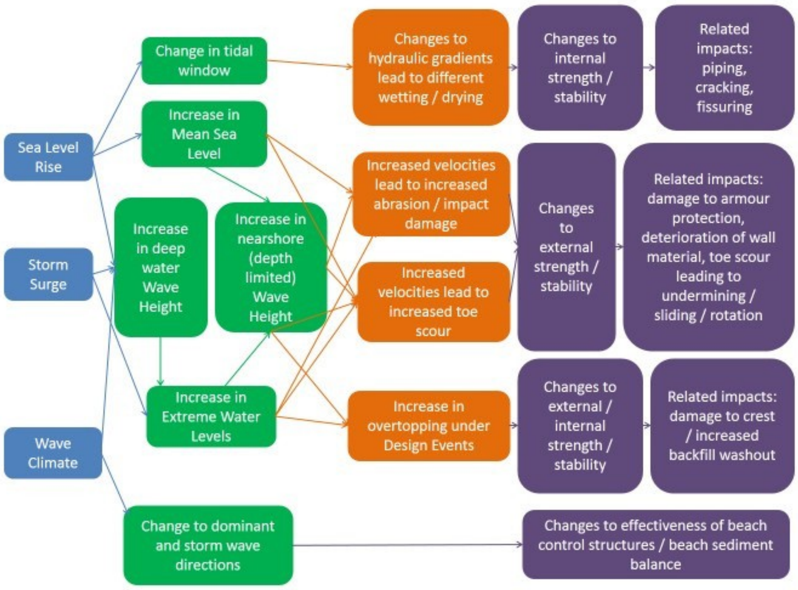
None

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Low**
- In the impact that a given change in climate will have on FCERMi: **Low**

In combination changes and context specific impacts

The impact of climate change at the coast will vary depending on the in-combination nature of the change and the specific design of the coastal infrastructure and its function. A simple overview of this interaction is presented below (Environment Agency, 2014).



Source: Environment Agency, 2014

Figure 4 A simple overview of the interactions between climate change and the impact on coastal infrastructure

Summary implications for FCERMi

Soft path coastal infrastructure – Utilizing natural infrastructure systems

As part of the on-going Environment Agency study into the potential impact of climate change on FCERMi, natural assets were assessed using the qualitative methods developed by the Standing Conference on Problems Associated with the Coastline (SCOPAC). The resulting expert based view classified coastal landforms as being at 'High', 'Medium' and 'Low' risk from climate change. Although of course subjective, the resulting relative sensitivity is useful and shown below.

Table 7 Impact of climate change on coastal landforms - A relative scoring

Landformtype	Climate change sensitivity			
	Sea level rise	Storm surge	Precipitation	Wave direction
Simple cliff	High	Moderate	Moderate	Low
Simple land slide	High	Low	High	Low
Composite cliff	Moderate	Low	Moderate	Low
Complex cliff	Moderate	Low	High	Low
Relict cliff	High	Low	High	Low
Embryonic dunes	High	High	Low	Low[1]
Fore dunes	High	High	Moderate, impacts on vegetation	
Climbing dunes	Moderate	Moderate		
Relict dunes	Low	Low		

Parabolic dunes	Moderate	High	Low	
Transgressive dunes	Moderate	Moderate	Low	
River deltas	High	High	Moderate	Moderate
Tide dominated	High	High	Low	Moderate
Wave dominated deltas	High	High	Low	High
Shore platforms	High	Moderate	Low	Low
Sandflats	High	High	Low	Moderate
Mudflats	High	High	Low	Low
Pioneer saltmarsh	High	High	Moderate impacts on vegetation	Low
Saltmarsh	High	High		Low
Sand beach	Moderate	Moderate	Low	High
Shingle beach	Moderate	Moderate	Low	Moderate
Mixed beach	Moderate	Moderate	Low	Moderate
Composite beach	Moderate	Moderate	Low	Moderate
Boulder beach	Low	Low	Low	Low
Barrier island	High	High	Low	High
Barrier beach	High	High	Low	High
Spit	High	High	Low	High
Cuspate foreland	Low	Low	Low	Low
Notes: Sea level rise = sensitivity to accelerations in the rate of sea level rise. Storm surge = sensitivity to changes in intensity/frequency of storm surges (will depend upon exposure of site). Precipitation = sensitivity to changes in pattern/intensity of precipitation				

Source: (Environment Agency, 2014)

Hard path coastal engineered assets

The Environment Agency study (2014) also provides an initial qualitative exploration of the climate change impacts on engineered coastal structures. These findings are summarized below.

Vertical Seawalls *(including concrete, brick and masonry, timber, anchored and cantilever sheet pile walls)* - Increases in sea level and storm surge may increase flow velocities resulting in toe scour / damage to armour protection and increased abrasion / impact of the wall material. The extent of damage will relate to the wall material and founding ground conditions. Toe scour can in turn lead to increased risk of undermining / sliding / rotation. Changes to wave climate and storm surge leading to increased wave heights and extreme water levels will lead to increased overtopping under design events. Where the crest or rear face is not protected this can lead to crest damage and washout of backfill material.

Primary climate sensitivities

- Increased sea level (Low)
- Increased storm surge (Medium)
- Changes to wave climate (Medium)

Earth Dykes / Embankments *(including with and without slope/crest/toe protection)* – Increased sea levels will change tidal window and impact wetting and drying cycles. For structures with a permeable exterior cover this could lead to changes in the internal structure and stability of the embankment. Related impacts include piping, cracking and fissuring. As with vertical walls, increases in sea level and storm surge may result in increased velocities against the structure with similar consequences. Where front faces are unprotected, increased toe scour and abrasion impacts would be more significant. Changes to wave climate and storm surge leading to increases incident wave heights and extreme water levels will again lead to increased overtopping. Where the crest or rear face is not protected this could lead to additional crest damage and washout of backfill material.

Primary climate sensitivities

- Increased sea level – Medium (permeable exteriors), Low (impermeable exteriors)
- Increased storm surge – High (unprotected), Medium (protected)
- Changes to wave climate - High (unprotected), Low (protected)

Sloping Walls *(with and without slope/crest/toe protection)* - As with embankments, increased sea levels will change tidal windows and impact wetting and drying cycles. Related impacts include cracking and fissuring. Associated increases in flow velocities against the structure could, as discussed above, undermine stability. Where front faces are unprotected, increased toe scour and abrasion impacts would be more significant. Changes to wave climate and storm surge, leading to increased wave heights and extreme water levels, are likely to increase overtopping and, where the crest is not protected, additional crest damage.

Primary climate sensitivities

- Increased sea level (Low)
- Increased storm surge (Low)
- Changes to wave climate (Low)

Control Structures *(including rock groynes, timber groynes and offshore breakwaters)* - Increased sea level and storm surge may result in increased velocities. This is likely to reduce material strength and undermine stability (for example through increased abrasion of timber groynes by shingle). Changes to wave climate and storm surge are also likely to impact the effectiveness of control structures (to manage sediment transport) as well as increasing overtopping and beach drawdown.

Primary climate sensitivities

- Increased sea level (Low)
- Increased storm surge (Medium)
- Changes to wave climate (Medium)

4.5 Temperature, solar radiation and drought loading

Climate related variables of interest

Temperature influences the performance of FCERMi in a number of ways. For example in some of the coldest areas of the world, such as Canada and the Baltic states, watercourses, and even the sea, can freeze. When rivers freeze conveyance is lost, significant bed and bank scour can occur and ice blocks can significantly damage structures and mechanical assets. Perhaps the greater threat however is manifest through an increased rate of deterioration that responds to a combination of temperature, drought and solar radiation. For example:

- *Spalling* – the influence of freeze-thaw processes on concrete and masonry are well documented (Crossman et al., 2003).

- *Loss of strengthen in surface cover* – Many embankments rely upon grass cover to provide protection from surface erosion. The ability of the grass to provide protection relies upon achieving a full surface covering or healthy grass (with a strong network root to reinforce the surface soils). Prolonged high temperatures (particularly if allied with drought) can weaken/destroy this cover and prevent the grass from recovering before the next flood. The combination of the high temperatures and drought, quickly following by flash flood events was a characteristic of 2012 (often colloquially referred to as the *'wettest drought history'*).

- *Desiccation and fine fissuring* - Fine fissuring in the surface soil structure can initiate flow paths and undermine the performance of a flood embankment (Dyer et al, 2009). High temperatures and drought can accelerate the desiccation process and set up a network of fine fissures in the surface soils.

- *Subsidence* – Drought loads and high temperatures can increase land subsidence, damaging urban FCERMi. This can be further stressed by groundwater movements (Jha, et al., 2012).

- *The performance of green infrastructure* – the performance of green infrastructure such as green roofs, SuDS and wetlands can all be influenced by extremes of temperature of droughts. Vegetation can wilt, infiltration can reduce and even unwanted species (such as mosquitos around standing water and SUDs) can be promoted.

- *Surface drying* - Solar radiation can dry the surface of soft cliffs (e.g. North Norfolk) can be an important contributing process in the erosion of soft cliffs and highlights that the evaluation of sensitivity of coastal systems to climatic change should not be done just for sea-level rise and increased storminess, but also for other climatic parameters (Bernatchez and Dubois, 2008; Bernatchez *et al.,* 2011).

Evidence of change

Karoly and Stott (2006) report a warming in Central England Temperature series, which is expected to increase further over the 21st century (Murphy *et al.*, 2009). 1^{o}C warming has been measured since 1980 (Jenkins *et al.*, 2008). UKCP09 data shows an increase in temperature and solar irradiation compared with historical data (Tham *et al.*, 2011).

A number of studies (Blenkinsop & Fowler, 2007; Vidal & Wade, 2009; Rahiz & New, 2013; Burke, et al., 2010) highlight the uncertainties associated with future drought loadings. All generally point towards an increase in droughts but with a wide range of estimates for their duration, severity and spatial coherence.

Changes of most interest and their potential impact on FCERMi

Mean temperature

This is generally considered unlikely to have a significant impact on asset performance.

Associated Tipping points

None – A change in mean values of 1 or 2^{o}C (or even 3-4^{o}C) is unlikely have significant direct impact.

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **High**
- In the impact that a given change in climate will have on FCERMi: **High** (i.e. sensitivity is low)

Extreme temperature

An increased frequency, intensity or persistence of extreme hot and very cold weather will affect FCERMi and exacerbate the impacts introduced above, for example:

- *Concrete structures* – Concrete FCERMi, like other infrastructure, are likely to deteriorate faster if they experience more frequent and extreme periods of the freeze-thaw.

- *Earth embankments* - Prolonged hot dry periods are likely to accelerate desiccation of surface soils. Little evidence is available for the likely impact of this as yet.

- *Mechanical and electrical structures* - Extreme hot and cold temperatures can act to restrict or even stop M&E assets from operating. There is little evidence currently available on the influence of extreme temperatures, the influence on FCERMi assets and the likelihood that they will be needed during these periods.

- *The performance of green infrastructure* – Green infrastructure represents the use of natural processes to carry out functions that have in the past been solely linked with the built environment. Green infrastructure is especially appropriate for use in flood risk management as flood plains have a natural storage capacity and slowly release floodwaters, reducing peak flood flows downstream. Working with natural processes in flood risk management means protecting, restoring and emulating the natural regulating function of catchments, rivers, floodplains and coasts. Central to the idea is working with the river and coastal processes (and flooding) rather than against them. "Soft path" infrastructure (e.g. green roofs, wetland storage, shelter belts, urban ponds, floodplain reconnection etc.) and "hard path" infrastructure measures (e.g. bypass channels, controlled storage in urban parks etc.) are both important aspects of modern flood management. High temperatures and drought can influence the performance of such infrastructure, particularly soft path measures, significantly reducing the ability for infiltration, altering the mix of the vegetation and/or encouraging the formation of standing water and associated undesirable outcomes such as disease or increased mosquito population (Armitage, et al., 2012).

Associated Tipping points

Hot and dry countries already successfully build and maintain FCERMi and it is difficult to envisage specific tipping points. Having said this, changing temperatures will influence design, for example the role and nature of green infrastructure in future climates.

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **High**
- In the impact that a given change in climate will have on FCERMi: **Moderate** (i.e. sensitivity is low)

Summary implications for FCERMi

Beyond the general points introduced above specific implications or requirements for modifications remain difficult to identify.

4.6 Problematic invasions and bacterial attacks

Climate related variables of interest

Changes in climate (e.g. associated warmer water temperatures, shorter duration of ice cover, altered stream flow patterns, increased salinization, etc.) will alter the pathways by which non-native species enter aquatic systems (Rahel and Olden, 2008). For example fish-culture facilities and water gardens are likely to expand, and potentially facilitate, the spread of non-native species during floods. Climate change will influence the likelihood of new species becoming established by eliminating cold temperatures or winter hypoxia that currently prevent survival. The construction of dams and reservoirs, a potential consequence of seeking greater security from floods and droughts, are also likely to serve as hotspots for invasive species. Climate change may also modify the ecological impacts of invasive species by enhancing their competitive and predatory effects on native species and by increasing the virulence of some diseases. Although most researchers focus on how climate change will increase the number and severity of invasions, some invasive cold water species may be unable to persist under the new climate conditions.

Evidence of change

There is limited objective evidence for the interaction between climate and problematic invasions and bacterial attacks. There are various empirical sources that highlight the linkages however as discussed here.

Changes of most interest and their potential impact on FCERMi

The vegetation, microbes and nutrients present within marine and fresh water systems are important components of the FCERMi system. Vegetation within watercourses needs to be managed to maintain conveyance and avoid blockage; marine vegetation can provide important buffers against erosion at the coast and nutrients and microbes can attack concrete and steel structures. The nature and intensity of the vegetation, nutrients and microbes reflect, in a large part, the prevailing local and global climate. As such they are included here as a legitimate climate driven loads. In this context the two variables that are of most interest are microbes and invasive species.

Microbes

Accelerated low water corrosion (ALWC, the attack of concrete and steel structures by nutrients and microbes in the marine and estuarial environment) is an important influence on the performance of flood defence structures (Melchers, 2014). Infrastructure in tidal and brackish water, such as the Thames Estuary are particular susceptible to ALWC and can experience rates of corrosion exceeding 1mm/side/year (CIRIA, 2005); a rate that is expected to increase with higher temperatures (Stewart, et al., 2011).

Invasive species

Conveyance of river channels, afflux at structures and the stability of flood defences can be significantly influenced by invasive species such as Japanese Knotweed (Defra, 2013). The preferential growth and survival of such species can be influenced by their adaption to conditions of high temperatures or drought. International climate change has been associated with the potential increase in more aggressive, non-native, animal burrowers that undermine the stability of flood defences. Currently no evidence exists to suggest this is occurring in the UK.

Associated Tipping points

Tipping points are likely to be site and species specific.

Confidence in our understanding

- In the climate change signal (in the context of FCERMi): **Low**
- In the impact that a given change in climate will have on FCERMi: **Low** (i.e. sensitivity is moderate)

Summary implications for FCERMi

Beyond the general points introduced above specific implications or requirements for modifications remain difficult to identify.

4.7 In combination events and interdependencies

In combination events – spatially coherence and sequenced

Flooding in 2007 and the more recent winter floods (2013/14) have highlighted the need for infrastructure to performance when exposed to storms that persist for many months, are widespread and apply multiple loads (intense rainfall, high river levels, groundwater levels and even coastal storms simultaneously). This presents significant challenges for the concept of the 'design storm' and demands that it is recognized (see Section 6). Equally it places a focus the performance of the infrastructure system, demanding more comprehensive view of the interactions between more elements of the flood defence infrastructure.

Infrastructure interdependencies

Few individual components of infrastructure perform alone; but rather rely on the performance of the infrastructure system as a whole to provide protection. Infrastructure interdependencies therefore play a very vital role in climate change risk and adaptation. In a technologically advanced world infrastructures are becoming more interdependent (Rinaldi et al., 2001) and redundant (backup) infrastructure systems are adding robustness, which ultimately improves tolerance to adverse impacts. But interdependencies also trigger failure cascades across systems amplifying disruption impacts (Rinaldi et al., 2001). For an extreme weather event risks analysis it is important to consider different interdependencies (physical, geographic, cyber and logical) between infrastructures that affect the economy and society (Pant et al., 2014). For example most infrastructures depend upon electricity, which means an electricity disruption has knock-on effects across other sectors leading to widespread disruptions (Pant et al., 2014). Hence investment in flood defenses around electricity assets benefits the wider economy and society. In the UK there has been underinvestment in critical infrastructure over the last two decades, which in turn has resulted in infrastructure that is less capable of assisting the UK economy to grow (Kelly et al., 2013). This has adverse effects on the climate risk preparedness also.

5 Likely future investment costs and opportunities to adapt

5.1 Challenging the basis of traditional design

Over the winter of 2013/14 the UK experienced very large surge events, coinciding with large spring tides on the east coast, sequences of wind and wave events that have battered the south and south-west coast and energetic long-period swell wave events have also had an impact on the south coast.

As a consequence, there has been increased structural damage to sea defences including soft defence features such as Chesil Beach. Equally the persistent storms have highlighted some particularly frailties within fluvial defences. Although little forensic analysis is yet available, anecdotal evidence suggests the succession of storms has driven significant toe scour, eroded surface cover and maintained persistent head differentials with the potential to drive internal erosion. Urban drainage systems (piped and surface storage services) and pumped catchments have also been overwhelmed, in part reflecting the severity of individual storms but also the increased percentage of run-off from saturated soils during the more moderate storms seen in this period. Increased frequency of 'on-the-demand' use, seen through 2013/14 is likely to be a feature of future climates (Wild et al 2013), will restrict the window for significant maintenance and repair with potential impacts on reliability of performance.

The conclusion must be that the focus on extreme events is necessary but not sufficient – and that the notion of a single design storm is dead. Under a changing climate designs will need to be based upon 'events' that might be single occurrences of high magnitude, for which classical extreme value theory would be relevant or sequences (uncorrelated) or clusters (correlated) in which individual occurrences may not be particularly large, but nonetheless lead to significant damage (Karunarathna et al, 2014). What is needed is a way of expressing this family (which may have further members to those identified here) as a collective framework, including consideration of rising mean sea levels, and embedding this in risk assessment and design methods, using a language that is clear to the public.

The complex nature of these loads now being experienced (and may be increasingly so) increases the need to take a systems approach, considering soft or hard and soft path defences (green and grey infrastructure) together. At the coast whilst re-alignment and abandonment are always difficult choices, impacting, as they do, on local interests and livelihoods, building resilience at an affordable cost around our coastline is going to require that such options form a part of our coastal management planning. However being forced to abandon a length of defence or implement an emergency repair is never a good option. This invariably limits the future options and in the worst cases can exacerbate problems locally. We need to be more assertive in determining where there may be a need to abandon defences and work with local stakeholders to develop long-term solutions that minimise the losses of those who are most directly impacted. This stresses the continued need for and development of of strategic Shoreline Management Planning and Catchment Flood Management Plans that are both brave and innovative.

5.2 Likely future investment costs

Little comprehensive analysis has been completed on the impact of climate change on FCERMi investment and how this might modify the protection they offer or the costs of building new and maintaining existing assets. Where partial analyses have been completed (most recently through the Environment Agency's Long Term Investment Strategy, Environment Agency, 2009c for example) the suggestion is that investment will need to be increased considerably over the coming 25 years. An ongoing (as yet unpublished study by the Environment Agency into the vulnerability of FCERM assets, Environment Agency, 2014) concludes '*it is quite conceivable that the level of investment needed to address it [climate change] could be double that at present.'*

This is a conclusion supported by the Foresight Future Flooding Studies that highlight the continued importance of engineered infrastructure to all four future scenarios explored (Evans, et al., 2004). As part of Foresight studies it was estimated that by 2080 annual investment in maintaining and replacing engineering infrastructure would need be £250m per year and £1,000m per year more than today (requiring year-on-year annual increments to reach these levels would be £6.25m and £25m respectively).

More recently studies such as the Environment Agency's Long Term Investment Plan are starting to explore the trade-off between varying levels of investment and changing flood risk for England. Within the Thames Estuary 2100 studies a wide range of climate futures and flood management responses where explored. As expected given the over designed nature of the current system , a flexible strategy was developed where the future expenditure reflects the reality of the future climate change with little upfront investment required now to purchase that flexibility (Tarrant & Sayers, 2012). As for England, in Scotland, Wales and Northern Ireland there appears to be little information of the likely future costs.

Increased costs are likely to be accrued through, for example:

- **Enhanced maintenance** – including (i) increased recycling and recharge, (ii) more frequent on-demand use and associated maintenance costs, (iii) more vigorous vegetation growth, (iv) management of surface covers – including grass and concrete.
- **New build costs** - where appropriate sea level rise and changing rainfall/flows will demand new/improved defences.
- **Purchasing future adaptive capacity** - Strengthening foundations, land banking, multifunctional designs/use.

5.3 Where do the primary opportunities to adapt lie?

In a general sense the objectives of adaptation are well known, for example:

- ensuring infrastructure is resilient to potential increases in extreme weather events, such as storms, floods and high temperatures (see for example Schultz et al, 2012);
- ensuring investment decisions take account of changing patterns of consumer demand, as a result of climate change, in areas such as energy and water use, travel, and consumption; and

- building in flexibility so that infrastructure systems can be modified in the future without incurring excessive cost.

The sections below discuss some of the underlying considerations and opportunities in more detail.

Soft path ('green') infrastructure: Better design and implementation

Promoting, and giving room to, natural infrastructure (beaches, channels, woodlands, floodplains) as a valid component of FCERMi. Ecosystems are therefore legitimate flood management infrastructure as well as providing critical provisioning, regulating and cultural services (Sayers et al, 2014). "Soft path" green infrastructure (such as land use management and run-off control in rural and urban areas, catchment and local storage such as wetlands and urban ponds, and floodplain reconnection etc) together with selective "hard path" measures (such as bypass channels, controlled storage etc) offer opportunities to simultaneously manage flood risk and promote ecosystem services (Figure 5). This is a synergy all too often overlooked and there are very few examples where this is actively pursued. To make gains in promoting soft path green infrastructure (and the dual benefiting for safeguarding and promoting ecosystems through flood management) will require a shift in emphasis. Working with natural processes needs to become a much more central consideration – a requirement acknowledged for example with the recent initiative of the Environment Agency in England to promote the concepts of working with natural processes in flood risk management (Environment Agency, 2012) and the recent adoption of 'natural flood risk management' into Scottish legislation (SEPA, 2012).

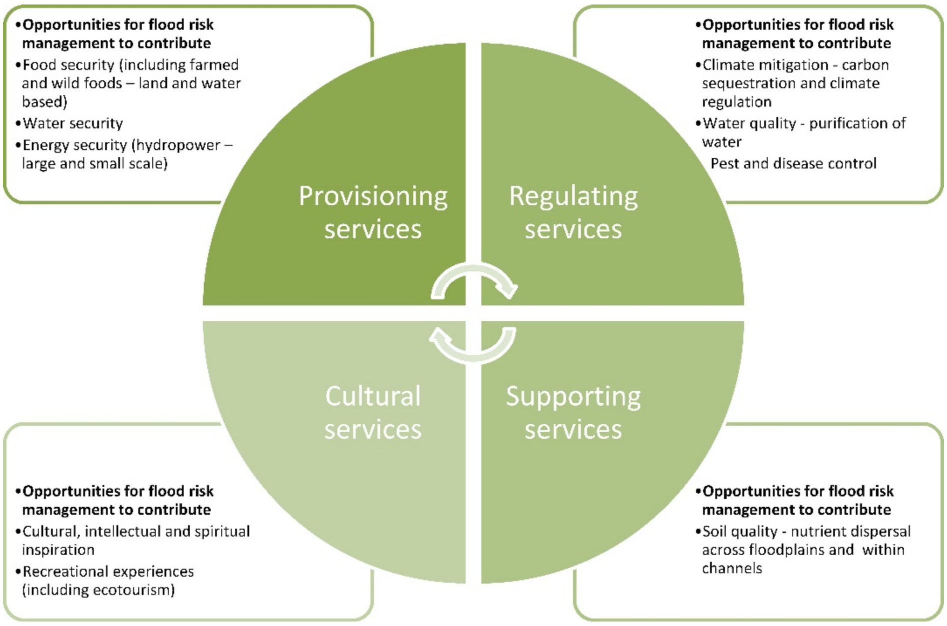


Figure 5 Soft path 'green' infrastructure can act not only to help reduce the chnage of flooding but promote wider ecosystem benefits (Sayers et al, 2014)

Working with natural processes and ecosystem functions also provide a natural hedge against climate change as natures own infrastructure has some capacity to autonomously adapt. Natural infrastructure is, if given room, better able to respond to changes in climate (helping slow down and store water closer to source, responding to sea level rise etc.).

Hard path ('grey') infrastructure: Better design and implementation

New designs and strategies provide the opportunity to provide infrastructure that is future ready. This might include for example:

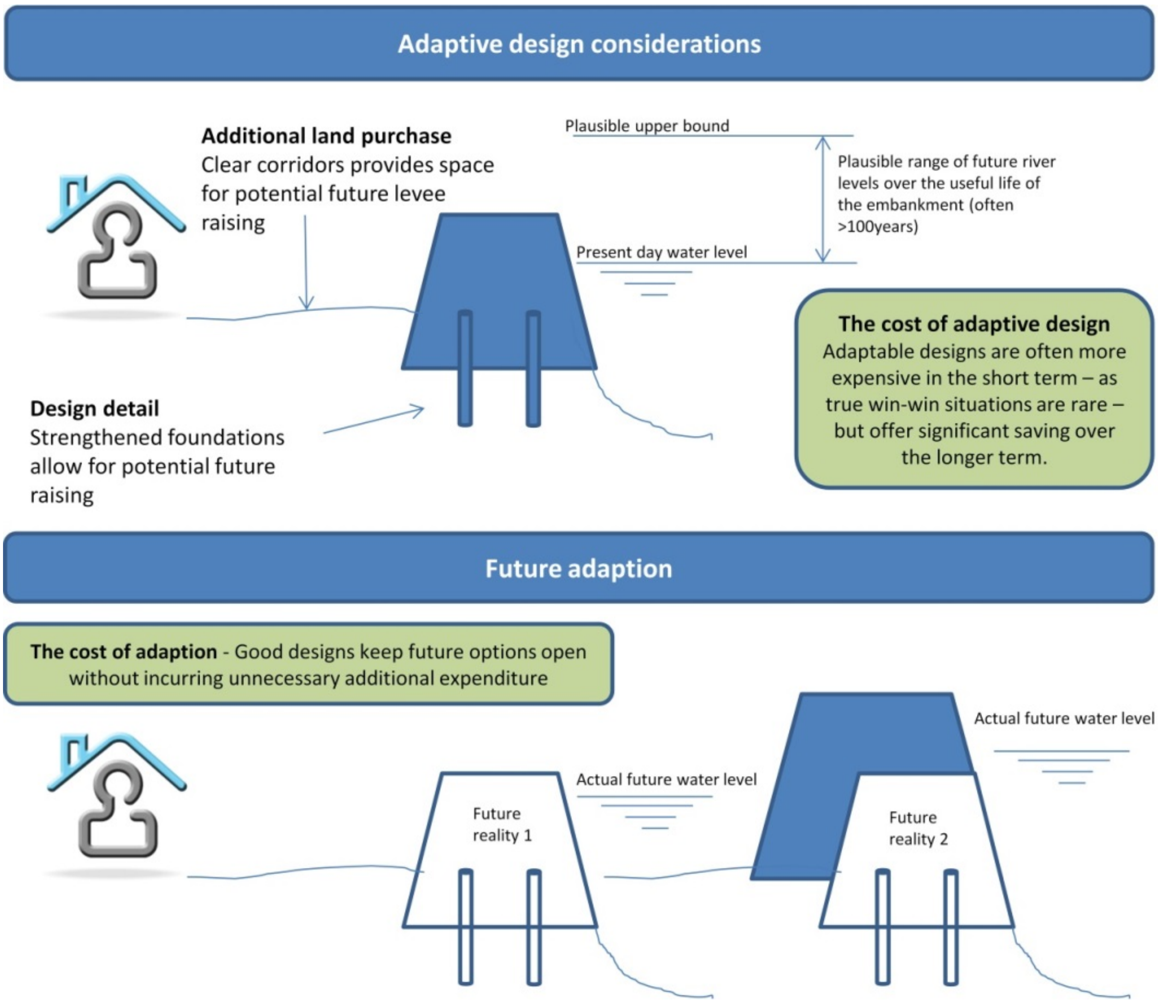
- **Design codes** – Design codes are rarely updated – reflecting the effort devoted to their creation and the capacity for update. Adapting to climate change may require that this process is revised; both in the way design codes are written and updated.

- **Greater precautionary in critical locations** - responding to a lack of knowledge in future loads through a raised level of precautionarity, although this is likely to raise costs. These could be major facilities in vulnerable locations (e.g., critical bridges and evacuation routes).

- **Adopt shorter design lives –** Anticipating the need for future modification and replacement may be an option in some settings – but of course is could be promote a negative public reaction resulting from more frequent retrofits and the perception of money 'wasted'.

- **Hedge by 'making ready' for future modification** – strengthening foundations, land banking and wider crests are examples of design features that make infrastructure 'future ready' (Figure 5). Developing an understanding of a much wider set of design modification to prepare FCERMi for future change is an important research challenge.

- **Transformational design practice** – The above focus largely on progressive changes in design practice. To deliver resilience infrastructure that is effective and efficient will increasingly demand transformational approaches (beyond the simple consideration of foundation strengthening and crest raising). The detail of what these transformational changes look like is unclear, but some examples are emerging. For example the multiple functional defences that provide parking, recreation and defence (as seen in the Netherlands, or recently in Colwyn Bay), through to the creation of urban storage and preferential flow pathways. Understanding the performance in extreme and unforeseen events (designing for exceedance) will no doubt form part of these considerations (see for example Sayers et al , 2012a&b).



Source: (Sayers et al, 2012b)

Figure 6 Adaptive design keeps future options open without incurring unnecessary additional expenditure

Adapting the urban infrastructure

Preparing new build:

- **New build in the floodplain** – It is perhaps unreasonable to expected that floodplains and areas prone to coastal erosion will become no –go areas for development; in many areas this would simply be unacceptable socially and economically damaging. However it is quite realistic to expect that all new buildings be constructed to be more flood resilient (White, et al., 2013)

Adapting existing building stock:

- **Retrofitting or modifying individual property scale FCERMi** – The Adaptation Sub-Committee (2011a) *noted that 'Buildings are a priority area for adaptation, because decisions concerning the design, construction and renovation of buildings are long lasting and may be costly to reverse'*.

- **Retrofitting or modifying landscape scale FCERMi** – Over longer timeframes it is realistic to retrofit at the landscape scale – not just upsizing traditional urban drainage systems, but transforming the built and rural environments to be more water sensitive. This might include a range of measures from impermeable paving, green infrastructure, small scale storage ponds, using streets as temporary flood pathways etc. Individually the measures may offer limited benefits, but given sufficient change over long periods their cumulative benefits should become clear.

- **Retrofitting or modifying engineered, planned and managed FCERMi** – Modification, often involving crest level raising, existing defences or embankments is only possible if the original foundations or structure are sufficient to support the modifications. One mechanism for reducing the loads on defence structures is through effective management of water courses and beaches by making space for morphological changes via realignment and restoration of floodplains, beaches and dunes.

Adapting existing infrastructure and maintenance activities

Given the significant sunk investment within existing infrastructure systems the majority of the UKs infrastructure stock will be in state of operation. The most significant response to the impacts of climate change is therefore likely to come through changes in maintenance practices. These changes involve incorporating responses to more extreme weather events into routine operations, improving collaboration with emergency managers, recognizing emergency management as an integral function of managing infrastructure.

In this sense, the management of some infrastructure (particularly natural assets such as beaches and vegetation in channels) is inherently adaptive. Changing maintenance practice of fixed structures is much more difficult to modify (in a way that is both effective and efficient) unless a pathway for future adaptation has been specifically designed in.

Promoting more adaptive and innovative strategies

It is widely recognized that there are many vulnerabilities within the infrastructure system, and it is impossible to cover the cost of all adaptation measures needed for complete resilience (RAE, 2011). As such it is necessary to prioritize the various pinch points where improved resilience is needed, either through laying the foundations for future adaptation or building in an appropriate degree of precaution today (or a combination of both).

Existing appraisal guidance does not explicitly take account of the value added by considering flexibility in the decision making process and therefore does not currently incorporate this potential contribution to adaptive capacity. However, guidance on the appraisal of FCERMi includes some guidance about accounting for future change and uncertainty, based on the use of decision trees and the application of Real Options Analysis. More recently these approaches have been extended to provide practical guidance on how to value adaptive capacity in options appraisal and will hopefully promote wider take up (Environment Agency, 2014).

6 Broader drivers and responses

6.1 How might socio-economic change influence FCERMi?

Infrastructure assets tend to yield value as an input to the production of something else. Commentators in the US point out that as a result, from time to time, basic maintenance and repair of infrastructure has received low public priority, a fact that may leave infrastructure even more vulnerable to climate-induced damage (Neumann & Price, 2009). This is equally true here.

The management of some infrastructure (particularly natural assets such as beaches and vegetation in channels) is inherently adaptive and is likely to change autonomously. The design and management of fixed engineered infrastructure is less easily modified and this is likely to require some form of incentive to promote adaptation. This could be through the funding rules or planning approaches for example.

6.2 Cross-sectoral independencies

Joint planning – Development planning

Local authorities face difficult trade-offs when planning future development. The costs to the local economy of constraining development in areas at risk from flooding or erosion (now or in the future) can be significant. Often either opposing demands to develop brown field sites or the lack of alternative sites mean there is little choice. This is not an excuse for failing to plan for the long term. FCERMi is often a central feature in Catchment Flood Management Plans, Shoreline Management Plans and Strategies but it is unclear if these studies are sufficiently innovative and sufficiently influential to modify local authority development plans. The ASC (ASC, 2011a) noted that:

- *Although they found some evidence of long-term, strategic planning for adaptation, such as Shoreline Management Plans, it was unclear how influential these initiatives were on local development plan policies and actual development decisions.*

- *They also found limited evidence that local authorities were factoring in long-term costs when making decisions on the strategic location of new development in their Local Plan. Local authorities should take a strategic approach to managing vulnerability at the scale of communities as well as at the property level. This will require explicitly weighing up the long-term costs of climate impacts against social and economic benefits from development that are more immediately released.*

Joint planning – Critical infrastructure and service providers

FCERMi does not stand in isolation. It is not constructed for its own intrinsic value but to provide wider benefits to society (through the protection it provides and the functions its supports). As such FCERMi is inextricably linked with the provisions of critical infrastructure and associated services (ICT, energy, health etc.). The impact of a failure within the FCERMi can extend far beyond the footprint of the physical floodwaters. Understanding the spatial cascade of impacts through infrastructure networks (Brown & Dawson, 2013) is therefore an important component of the providing effective FCERM and the engineered actions taken to

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prevent the cascade (and potential escalation) of impacts should be considered to make a legitimate contribution to FCERMi. The way in which flood risks propagate through large interconnected systems is currently the subject of the ITRC (www.itrc.org.uk) research programme; this is an area of research that is likely to remain active.

Road networks that provide safe access and egress for communities during times of flood are equally starting to be seen as a part of the FCERMi. Ensuring they continue to operate during extreme events is an important concept of build a resilient community.

Encouraging resilience new and retrofit properties

Property owners can act to increase the demand they place upon system scale infrastructure or reduce it (Defra, 2012). For example by improving their resilience to future changes in climate (by installing property scale resilience measures or making provision to protect the owner business functions from flooding or erosion risks) they can also impact positively on the infrastructure upon which they depend.

The Adaptation Sub-Committee (2011a) highlight that there is limited evidence on the uptake of adaptation measures in the retrofit or repair of existing properties. This is despite a number of reasonably low-cost measures for existing buildings (£500 to £2,500 per property) that avoid significant damages from modest flood levels being available (including airbrick covers, door guards, re-pointing external walls, main sewer non-return valves, drainage bungs and toilet pan seals, etc.).

Householders and developers require the right incentives to take action. The ASC's second progress report found instances where there is either a lack of or misaligned incentives, both of which lead to an inefficient adaptation outcome. Levers other than regulation, such as insurance incentives and better information, may be more important for existing homes. There is no evidence of any specific programmes in Scotland to support the retrofitting of existing buildings to improve their resilience to
future climate risks (Adaption Sub-Committee, 2011b).

the update of new SuDs and refotting SuDs into existing urban development remains a difficult process but will need to be encouraged to promote resilience.

6.3 How might technological change influence FCERMi?

Better understanding of the reliability of the infrastructure, its time-dependent deterioration and the impact of changing loads will all be needed to support better adaption choices.

New approaches to the design and construction of flood defences (Anvarifar, et al., 2013) are seeking to provide multiple uses and benefits. Similarly there are a wide range of propositions for redesigning houses and towns (Casey, 2012) from raising houses onto stilts through to floating artificial islands communities. These measures all intend to help society 'live with water'.

Pervasive sensors and the move towards real time monitoring of condition and loads could provide a significant contribution to more targeted maintenance and emergency response.

Although not specific to climate change, pervasive sensors offer opportunities in present climates too, a greater confidence in being able to identify and respond to prevent potential failures may promote the update of adaptive management and lead away from a bias towards design conservatism and precautionary allowances (that may lead to mal-adaptations).

6.4 Is FCERMi provision already changing as a result of climate change?

Development planning and individual properties (new and retrofit)

A review by the Climate Change Adaption Sub-Committee (Adaptation Sub-Committee, 2011) of land use change over the last ten years in eleven local authorities and local authority development applications in 2011 found that:

- *Development in areas of flood risk increased in eight of the nine local authorities at risk from river and coastal flooding and in four of them the rate of development was higher than across the locality as a whole.*

- *Three of the four coastal authorities saw an increase in development in areas of eroding coastline, and in two of them the rate of development on unprotected coastline was higher than across the authority as a whole.*

- *The area of hard surfacing increased in five of the six urban authorities studied, primarily at the expense of urban green space, which declined in all six authorities. This is likely to exacerbate surface water flooding and demands placed upon the urban drainage infrastructure*

- *Development applications sampled included variable levels of adaptation at the property level, from nearly all applications (96%) in areas of river and coastal flood risk to 55% of applications in areas of surface water flooding risk.*

- *Despite evidence of the uptake of the low-regret adaptation actions (flood resilience measures) in new homes there was much less evidence on the uptake of low-regret measures in existing homes. Since then the Green Deal and the Code for Sustainable Homes have become more established but there appears to be little evidence of further take up of adaptation measures across the buildings sector.*

This indicates that land use planning decisions may potentially increase the vulnerability of some areas to climate impacts. Equally, adaptation measures such as investment in flood defences and use of property-level measures can at least in part offset this vulnerability. However, development decisions may be locking in a legacy of future costs from the maintenance of infrastructure (such as flood defences) and impacts from residual climate damages. Questions remain as to how these costs will be met in the future.

Selection of infrastructure options

In part the limited adoption of more adaptive strategies within the FCERM industry is associated with difficulties in visualising exactly what these are and how they operate (Enviironment Agency, 2014). The advice concerning the generation of options assists by identifying attractive attributes of adaptive responses which should help ensure (although do not guarantee) that the associated option is resilient to future change or capable of modification. The list of attractive attributes is replicated below (Environment Agency, 2014):

Reducing vulnerability:

- *Have all reasonable opportunities to reduce vulnerability been taken?*
- *Have steps been taken to limit future increases in vulnerability?*
- *Has a full examination of the range of futures identified the potential for a significant increase in risk requiring a radical approach to managing the receptors?*

Making space for water:

- *Have opportunities to make space for water and function been maintained/ enhanced?*
- *In making space for water, can the scale of the receptors at risk be reduced?*

Delivering co-benefits and co-funding:

- *Have opportunities for present day co-benefits and co-funding been enhanced?*
- *Have opportunities for future benefits been maintained / enhanced?*

Preparing for change:

- *Has future modification been considered?*

Deferring/removing or abandoning:

- *Could it be removed / stopped with minimum impact on resources and the environment?*
- *Can investment be delayed without an intolerable build-up of risk or foregoing of current opportunities?*

In this context, response to climate change and future uncertainty is not to defend at all costs but rather explore and use a range of valid responses. In determining exactly what to implement, issues of affordability/ability to finance will increasingly be central concerns and incremental adaptation will become important thus reducing the uncertainty about timing/lock in to solutions.

6.5 Is infrastructure provision socially equitable and will climate change influence this?

Infrastructure provision is not equitable; all FCERMi infrastructure acts to protect the few rather than the many. Often however those benefiting from the protection contribute wider economic and social benefits (employment, recreation, transport links etc). It is unclear how funding for infrastructure provision, climate change and appraisal changes will influence equity. Perhaps, a greater reliance on natural infrastructure developing multiple benefits over wider spatial scales might help reduce inequities.

6.6 Are innovations outside of the UK likely to influence our approach?

The ASC highlights that the UK's approach to adaptation compares favourably with progress in other countries. The UK is the only country to have established a legal framework for adaptation, which requires the Government to undertake regular risk assessments and prepare a National Adaptation Programme. Within Europe the UK is one of only three countries to have established a formal monitoring and review system for adaptation. The UK's climate projections are among the most advanced in the world and the formation of a statutory advisory committee that covers both adaptation and mitigation is unique.

The ASC go on to highlight that these institutional arrangements do not tell us how well prepared the UK is for climate change and that very few organisations feel that we are taking active steps to manage future risks. This suggests that capacity building has increased awareness of adaptation, but this has not yet translated into significant action – this conclusion appears to be very much reflected in the FCERMi sector.

In recent years a significant focus has been placed on developing resilient infrastructure and embedding adaptive thinking into infrastructure planning in the US, Australia and elsewhere. For example the US study into infrastructure resilience highlighted a number of barriers to adaptation that have resonance with challenges in the UK (U.S Department of Energy, 2012):

- ***Differences in planning horizons:*** *Although climate scientists describe the future in terms of outcomes that unfold over decades to centuries, the long-term planning horizons for transportation infrastructure rarely exceed 30 years. Therefore, transportation planners often perceive that the impacts of climate change will occur beyond the time frame of their long-term plans and fail to realize that today's decisions will affect how well the infrastructure responds to future changes in climate.*

- ***Treatment of uncertainty:*** *Climate change introduces uncertainties into the transportation planning process that make it difficult to plan and design infrastructure that can accommodate these impacts. In addition, these uncertainties are unfamiliar and uncomfortable for many planners. Climate scientists often describe the future in probabilistic terms, whereas transportation professionals typically focus on knowns. This narrow focus represents an obstacle to developing dynamic decision making processes that can adapt to new information and accommodate feedback as knowledge about climate change develops over time.*

- ***Poor alignment between climate change impacts and transportation organizational arrangements****: The decentralized and modally focused organizational structure of the transportation sector may not align well with climate change impacts, which do not always follow modal, jurisdictional, or corporate boundaries.*

- ***Resource constraints:*** *Climate change in some U.S. regions may necessitate permanent, expensive changes. Many infrastructure management agencies are already financially stretched, a reality highlighted periodically in the media after catastrophic infrastructure failures.*

- ***Resistance to change:*** *Transportation professionals typically adopt incremental rather than radical solutions when faced with a new problem, such as a break from a historical trend. This may hamper timely responses to issues such as climate change that involve risk and uncertainty.*

- ***Lack of relevant information:*** *Transportation planners often lack sufficiently detailed information on which to take appropriate action. Although climate scientists tend to describe projected changes in climate in terms of global, continental, or sub-continental averages, transportation planners need data at a finer level of geographic detail because infrastructure is regional and local.*

7 Overall confidence in the science

To date the science of climate change has largely focused on the driving loads and the end impacts (changes in risk, as in Foresight and other studies). Little effort has been devoted to the influence on the change performance of the FCERMi beyond the obvious (changing overtopping rates or overflows etc.). The complex and more subtle, but significant, impacts on infrastructure discussed here have had little serious scientific study and rely upon engineering judgement and subjective reasoning. Having said that, many of the impacts discussed are undisputed, with the lack of confidence being driven by the climate projections themselves (particularly around extreme values, sequencing of loads etc. that are, with the expectation of mean sea level rise, much more important than mean values) and the engineering understanding of infrastructure response to these.

8 Research gaps and priorities

- **Promoting a focus on adaption at the planning and design stage** - Adaptation activity in the UK has been underway for nearly twenty years. Early reports from the ASC (Adaptation Sub-Committee, 2010) suggested that a large number of early studies on UK adaptation had made progress in building capacity and raising awareness but little had changed 'on the ground'. The FCERM sector has been better than most in identifying possible climate impacts (through studies such as the Long Term Investment Strategy (Environment Agency, 2009c) and the UK Climate Change Risk Assessment (Defra, 2012). Following from work in the TE2100 (Tarrant and Sayers, 2012) and the update of the Treasury Green Book to include a flood example (HM Treasury Annex A, 2011) the principles of making robust choices in the face of future uncertainty have matured within academic literature (Sayers *et al.*, 2012b) and crucially how these can be promoted within the current decision making framework (AdCAP work).This will require significant supporting guidance.

- **Developing quantified evidence based models and approaches** - Our understanding of the reliability of the infrastructure, its time-dependent deterioration and the impact of changing loads (and the interactions between these) is however only in its infancy. Significant research will be needed advance understanding and encourage the development of innovations in infrastructure design and management.

- **Understanding the performance of soft infrastructure** – Crucial to FCERMi is the role of soft infrastructure, such as green spaces in urban areas, beaches and mudflats. These systems make important contributions to the management of flood and erosion risks, and driven in part by the need to manage costs and reduce environmental impacts these measures are increasingly called for. Our understanding of their performance is incomplete however and key questions remain about their effectiveness over different spatial and temporal scales.

- **Identifying and communicating tipping points**–Various basic feedback loops are now well known (the relationship between sea level rise and increased wave heights etc.) and the aspects of the infrastructure design / climate change future that are potential tipping points. Moving beyond these rather high level statements towards quantified assertions remains some way off. It is, for example, unclear even if the vocabulary to describe a tipping point in the changes to spatial coherence or temporal sequencing yet exists.

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Appendix 1

Reduction in coastal dike Standard of Protection (expressed as return period in years) in 2080s due to climate change: Example for South-East of England (Sutherland and Gouldby, 2003)

Present SoP	World Markets	National Enterprise	Global Sustain-ability	Local Steward-ship
Vertical Wall				
2	<2	<2	<2	<2
5	<2	<2	<2	<2
10	<2	<2	<2	<2
20	<2	<2	<2	<2
50	<2	<2	2	2
100	3	3	4	4
200	7	8	10	9
Embankment				
2	<2	<2	<2	<2
5	<2	<2	<2	<2
10	<2	<2	<2	<2
20	<2	<2	<2	<2
50	<2	<2	2	2
100	2	2	3	3
200	4	4	5	5
Shingle Beach				
2	<2	<2	<2	<2
5	<2	<2	<2	<2
10	<2	<2	<2	<2
20	<2	<2	<2	<2
50	<2	<2	2	2
100	2	2	3	3
200	4	4	5	5