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Impact of climate change on asset deterioration

Report - SC120005/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

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Project Number:
SC120005/R1

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

The Environment Agency together with local authorities, internal drainage boards and various private landowners are reported to maintain £35 billion of flood and coastal erosion risk management (FCERM) assets. Over time these assets deteriorate and require maintenance to retain their standard of service and avoid failure. This project was established to develop information and methods that will help to support future decision making in this respect (e.g. advising national investment strategy planning), and to help inform where future efforts may need to be targeted.

With this research, we are increasing our understanding of how climate change factors may alter the vulnerability to deterioration of those assets. The project has looked at deterioration processes for 47 different FCERM asset types. Qualitative assessments for each asset type have been developed in the context of specific climate change factors and provide a core building block in assessing the potential vulnerability of those assets from climate change. These identify the key elements and deterioration processes likely to be affected by climate change and the factors that create that change in vulnerability.

The quantitative assessments also enable a relative categorisation of the potential vulnerability of each asset. From this, it is possible to prioritise which assets are likely to be most vulnerable to climate change, and to screen out those that are of less concern and do not warrant specific attention going forward.

Methods that begin to better quantify (either numerically or comparatively) the climate change impacts on asset deterioration have been explored. Illustrations of how to quantify some of the impacts have been developed, demonstrating the extent to which the climate change factors considered could alter the requirements for maintenance, repair or upgrading of particular asset types.

The above outputs collectively provide guidance that those considering asset deterioration at any level can begin to apply.

Approaches to calculate the overall impact of climate change upon asset deterioration have then been considered, and an initial high-level approach for determining the potential total value of this has been developed. Based upon data available at this time, it is estimated that current budgets for maintenance and repairs may need to increase annually by between 30% and 80%, some £30 to £75 million per year, to address the greater potential for deterioration. In addition to that, upgrading and improvements will be needed for the most affected assets, which could require investment of a further £2.5 to £4.5 billion over and above currently estimated rebuild or refurbishment costs.

It is apparent that just a small number of asset types make up 90% of the increased cost requirement, with embankments, walls and bank protection being the major contributors to these additional investment needs. This is a result of their specific vulnerability to the effects of climate change, combined with the unit costs to maintain and repair those asset types, and the sheer number of assets of those types that exist.

Depending upon our ability to respond to the levels required, other measures may also become appropriate or necessary to consider: for example, futureproofing new and replacement schemes so that they are resilient to these increases, proactively embarking on a major upgrading and improvement programme, or even considering changes to FCERM strategy in the long term.

Acknowledgements

Several individuals had an important role in the development of this project: in particular the Project Advisory Group who provided support, guidance and direction to the work, resulting in the outputs presented here, and a number of technical experts from CH2M who produced the assessments and analyses contained in this report and the supporting technical appendices. Key contributors from these two groups are listed below. In addition, the valuable contributions made by members of the Environment Agency and various local authorities in terms of data and advice that could be utilised by this project is appreciated.

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Contents

1 Introduction

1.1 Objective

The Environment Agency together with local authorities, internal drainage boards and various private landowners are reported to maintain £35 billion of flood and coastal erosion risk management (FCERM) assets (Environment Agency 2014). Over time these assets deteriorate and require maintenance to retain their standard of service and avoid failure. With this research, we are increasing our understanding of how climate change factors may alter the vulnerability to deterioration of those assets.

This project was established to develop information and methods that will help to support future decision making in this respect; for example, advising national investment strategy planning, and to help inform where future efforts may need to be targeted.

1.2 Background

Climate change could have significant implications on the rate of deterioration of FCERM assets. As these assets often have long operational lifetimes, they are sensitive not only to the existing climate at the time of their construction, but also to climate variations over the decades of their use. To increase the resilience of both new and existing infrastructure, we must be prepared and plan ahead to address the impacts of climate change on asset deterioration, not just performance.

Climate change is expected to become more pronounced in the future as emissions continue, but predictions of how this will affect us remain uncertain and cannot be reliably quantified just yet. This is because the climate system is very complex and because long-term projections of human activity and emissions are themselves inherently uncertain. Although recent climate variations are thought to be starting to have effects on many natural and human systems, the impacts have not yet become established trends. Nonetheless, it is possible to look at the nature of potential changes and different scenarios for the magnitude of those changes, to begin considering what some of those impacts might be and whether they give cause for concern.

The increased level of maintenance activity or asset upgrading that may be required to address increased deterioration associated with climate change is one such impact that needs to be considered. Securing a better understanding of the extent to which climate change may affect asset deterioration is going to be important to effectively manage those assets in the future. Improving the appreciation of any additional preventative maintenance which might be necessary to address climate change, or being able to build new assets that are more climate resilient, is going to be a vital part of long-term planning.

Although the effects of climate change are regularly considered in terms of scheme performance (e.g. the standard of protection provided by a structure against overtopping and flooding), up until now the effects upon deterioration of those same assets which may also lead to their service failure is less commonly analysed. It is that aspect that this project is addressing.

1.3 Project scope

For the purposes of this project, 47 different asset types (both natural and man-made) have been examined, including further subsets of those, across fluvial, estuary and coastal environments. These 47 correspond with the **definitions** of FCERM asset types listed in the Environment Agency's Creating Asset Management Capacity (CAMC) programme, although the information and analysis provided by this study is not limited only to assets managed by the Environment Agency; FCERM assets managed by local authorities and others are also included. The project concentrates upon how certain changes in climate, such as increased sea levels or river flows, may affect the process of asset deterioration for each of those asset types, and from that which assets are potentially most vulnerable to those changes.

An initial scoping phase explored the present state of knowledge and from that requirements for the project. Those requirements, which form the scope for this study, included:

- identifying how different asset types are vulnerable in terms of deterioration as a result of climate change, and the nature of that vulnerability
- providing some indication of the potential implications for those asset types, with identification of those assets that may require most attention going forward
- providing a means to establish, at a high level, an initial measure of the total potential impact

The scoping phase provided definitions, and outlined a range of approaches that might be adopted to deliver the requirements above. Those have been developed in the present study and are presented here.

1.4 Overview of content

This report includes the following sections:

1. **Introduction** – background to the project.
2. **Definitions** – including deterioration, what constitute FCERM assets and the climate change factors being considered.
3. **Asset assessment** – outline of the approaches taken to the various elements of the study, which are contained within the appendices.
4. **Assessment outcomes** – a summary of the findings and conclusions from the various elements of the study, for which details are found in the corresponding appendices.
5. **Establishing impacts** – description of the approach proposed to calculate the consequences of increased vulnerability, with a high-level estimate of the levels of investment required to address the issue and which asset types may be most affected.
6. **Conclusions** – summary of key findings, including discussion on high level impacts, together with recommendations for using the information, methods and results of this study.

In addition, there are four further technical appendices that support this report, as follows:

A. **Material degradation** – a synopsis of material degradation processes and investigation into rates from existing literature.

B. Asset deterioration assessments – mapping of the potential changes in deterioration for different assets as a result of climate change factors, including a qualitative assessment of the resultant potential changes in vulnerability for those asset types.

C. Quantification of vulnerability – appraisals of methods to quantify vulnerability and impacts from climate change on asset deterioration, including illustrative examples.

D. Impact analysis – appraisal of approaches to calculate the total impact of climate change on asset deterioration at a national level, including an approach based upon maintenance and repair costs, with the application of that approach and results presented.

2 Definitions

2.1 Deterioration

2.1.1 Descriptions

To have some common understanding, the following definitions are included here as reminders of the subtle differences between terms frequently used in the context of this topic:

- ***Deterioration**:* make or become bad or worse.
- ***Degradation***: wearing down (to disintegrate), reduce to a lesser form *[a sub-form of deterioration].*
- ***Performance**:* achievement under defined conditions *[in this case delivering on its design capacity/level of service].*
- ***Vulnerability***: that may be harmed, exposed to damage by.
- ***Impact***: effect or influence upon.
- ***Sensitivity***: potential to be affected by external stimuli, responsive to or recording slight changes *[this can be low as well as high].*
- ***Susceptibility***: likely to be affected by, liable or vulnerable to *[exposure to].*

In describing assets and the effects upon them within this study we use **degradation** to refer primarily to materials and component parts of an asset, with **deterioration** applying more broadly to the asset (see the following subsection). We use **vulnerability** to describe the potential for an asset to be affected by climate change, acknowledging that there are varying degrees of that, and **impact** as a measure of the consequences of that, which can apply at an asset-specific level but also aggregated up (e.g. to a national level).

2.1.2 Distinguishing between deterioration and performance function

This study just considers the deterioration of the asset as a consequence of defined climate change factors; it does not seek to quantify any change in standard of protection. By definition, in looking at deterioration of an asset we are taking account of a change in its ability to perform/function, and indeed some of the methods to assess deterioration may be the same as those used to determine protection/performance standard. But this is coincidence, not by design, and an important distinction to be made.

Climate change may affect the asset deterioration through producing:

- increasing rates of material degradation (e.g. spalling of concrete, corrosion of steel)
- increasing wear and tear of components (e.g. to moving parts in mechanical structures)
- increasing frequency of loading and damaging conditions to structural elements (e.g. erosion of embankment back slope through more frequent overtopping)

A general deterioration over time could mean increased maintenance to repair the asset, or it could mean that at some point in the future it will lose its integrity and ability to fulfil its function. In some cases, it could mean an increase in operational activities, for example the manual or automated control of mechanical structures.

Climate change may affect the asset performance function through producing:

- an exceedance of design conditions that result in the asset being overflowed by lower return period events
- an exceedance of design conditions that result in the asset no longer being able to accommodate greater flows

A change in performance characteristics may or may not however result in a deterioration of the asset itself, simply a lesser ability to achieve its function to the standards intended.

Table 2.1 provides a checklist of examples offering guidance on considering whether an impact from a change in climate is upon the asset's deterioration or performance.

Table 2.1 Deterioration versus performance

	Deterioration	Performance
Process	Deterioration may lead to and include structural failure e.g. • Degradation of materials • Deterioration of elements • Structural failure	A structure would not necessarily fail (i.e. it will still provide a function) but is no longer large enough or of sufficient capacity e.g. • Structure (e.g. embankment) too low to provide same standard of protection against higher water levels • Structure (e.g. culvert) too small to accommodate increased flows

Response	New or more work may be required to stop it falling over/falling to pieces
	e.g.
	• Increased maintenance requirement
	  ○ Repair/replace elements
	  ○ Frequency of operation
	• A need to upgrade the structure to ensure the structural integrity (such as adding an element, e.g. toe protection)
		A new capital scheme/structure required to make it larger or replace it to address the impacts of climate change on receptors
		e.g.
		• A need to raise the height of the structure to provide the same standard of protection
		• A need to increase capacity (e.g. put in bigger pipes)
		• More frequent operational requirements (e.g. flood gate closure)

2.2 Asset types

Although not limited just to Environment Agency assets, and applying also to FCERM assets that might be captured elsewhere, for example by local authorities, the Environment Agency's Creating Asset Management Capacity (CAMC) programme provides a set of definitions that can be used to describe and classify different asset types (Environment Agency, 2013). These definitions have been adopted by this study as they are inclusive of the range of FCERM assets across different agencies and environments.

Both man-made and natural FCERM assets are considered, but CAMC does not include all types of asset associated with water management (e.g. water supply and waste services, or reservoirs). The CAMC inventory system adopts a system of asset classification, with FCERM assets identified as shown in Table 2.2.

Table 2.2 CAMC asset type categories

Asset types				
Channel	Defence	Structure	Instruments	Buildings
Channel Crossing	Land	Beach Structure	Aids to Navigation	Major Civils

However, this higher-level classification was determined to be insufficiently refined to enable meaningful assessment of impacts, and consideration is necessary at the CAMC subasset level, listed below in Table 2.3. ***For the purposes of this study, these asset subtypes are simply referred to as the 'assets'***.

Table 2.3 Asset subtypes

Asset subtypes classification		
Asset subtype	**Asset subtype**	**Asset subtype**
Open Channel	Saltmarsh	Groyne
Simple Culvert	Mudflats	Breakwater
Complex Culvert	Washland	Slipway
		Steps
Bridge	Screen	Ramp
Utility Services	In Channel Stoplogs	
	Control Gate	Instruments – Active Monitoring
Embankment	Outfall	Instruments – Passive Monitoring
Wall	Weir	
Flood Gate	Spillway	Beacon
Demountable	Stilling Basin	Buoy
Bridge Abutment	Draw-off Tower	Signal
High Ground	Fish Pass	Signage
Quay	Hydrobrake	Dolphin
Beach	Inspection Chamber	
Dune	Jetty	Pump House
Barrier Beach		
Promenade		Abutment
Cliff		Central Pier

2.2.1 Further subcategorisation

There are many variables within several of the above- listed asset types which in many cases determine the extent of the impacts that climate change may have upon their deterioration. These include:

- composition of different elements and materials
- geometry and form of the structure
- setting

To illustrate this point, a single defined subasset is a ‘Groyne’. There are, however, many different forms of groyne; for example, rock mound or timber piled. Each has entirely different characteristics and therefore considerations with regard to its failure and deterioration processes; and thus, the potential impacts from climate change. Furthermore, within the category of timber groynes, the impacts on their deterioration may be very different if they are located on sand or shingle beaches.

Another example is that of a ‘Wall’. Quite different types of wall may be found along the edge of a river, in an estuary or at the coast. Of those at the coast, the configuration of these walls can be substantially different if they are providing flood protection or coast protection functions. In that same setting, even for a single material type, ‘concrete’, there will be reinforced concrete, mass concrete and blockwork walls, all of which can deteriorate in different ways and at different rates.

2.3 Climate change

2.3.1 Primary (hydrodynamic) factors

This project determined an approach that would consider four primary climate change factors. These were:

- Sea Level Rise
- Storm Surge
- Wave Climate
- Fluvial Flows (as a consequence of rainfall)

The above were considered to be those that would enable a robust appraisal of the potential vulnerability of FCERM assets, being (i) widely considered by the climate change community to be likely to occur, and (ii) able to be used to readily quantify their potential impacts on those assets.

However, this is by no means an exhaustive list of all the climate parameters that could possibly change in the future, and which could impact FCERM assets. Although other factors such as temperature and rainfall were not primary considerations for this study these are not dismissed and Sections 2.3.4 and 4.2.4 discuss these further.

The scale of the changes in these factors to be considered (albeit at this point purely for qualitative assessment purposes), presented in the subsections below, are based upon guidelines provided in *Adapting to climate change* (Environment Agency 2011), and as recently updated (Environment Agency 2016). Although guidance on these values will frequently alter as the science and understanding continually develops, it was considered that those values selected here are of an appropriate order of magnitude for the high level assessments from this particular study, and modest variations to those are not going to alter any of the information or conclusions from it.

Sea Level Rise (SLR)

While local analysis of climate change impacts of FCERM assets would be directed to use 2016 Environment Agency guidance (or its successors), for the assessment of vulnerability, the approach adopted here has been more pragmatic and proposes using more generic potential sea level rise projections. The magnitudes of change considered therefore are relative SLR increases of the order of 20cm and 50cm.

These are not intended to represent the full range of projections for the UK, but provide values that could potentially be realised in the relatively near term (e.g. in the next 40–50 years), and are expected to remain valid with future updates to SLR projections.

Storm Surge

Potential changes in storm frequency (return periods), intensity and tracks remain a highly uncertain feature of potential future climate change. To be consistent with the Environment Agency guidance, and in order to understand the potential vulnerability of FCERM assets to a change in extreme water levels, it was concluded that the appraisal assumes the potential for increases in storm surge elevations of the order of 20cm, in addition to the underlying sea level rise. This can be considered in a simple additive fashion; for example, for a 1 in 50 year event, use the present-day 1 in 50 year water elevation, plus SLR allowance, plus 20cm.

Wave Climate

There remains significant uncertainty over the impacts of potential future climate change on wind, and hence wave, climates, particularly for extremes, and any potential for shifts in patterns such as bi-modal occurrence. Similar to the approach recommended above for storm surge, it is concluded for this study that a 10% increase in extreme wave height is considered most suitable in order to investigate the potential vulnerability of FCERM assets to changes in wave height. This value is based on the 2016 Environment Agency climate change guidance, and in absence of any more recent specific/appropriate guidance is considered suitable for broad level consideration of vulnerability of FCERM assets.

Fluvial (River) Flows

Based on a range of studies, the most recent Environment Agency advice (2016) presents a range of regionally specific change factors that have been derived for UK river basins. These present a wide range of values for specific areas based on time horizon and climate scenarios. However, for this analysis of potential FCERM vulnerability at a high and generic level, a pragmatic approach has again been taken. Two values, representative of the range of change factors for the periods to 2020 and 2050, are considered appropriate for considering the potential magnitude of change; namely an increase in flood flows of 15% and 30%.

2.3.2 Climate change cumulative effects

As well as considering each climate change factor individually, it is important to look at the cumulative effects of these. Several of them lead to the same consequences in terms of changes in loading or force on the asset, as illustrated below in Section 2.3.3. Therefore, in considering deterioration processes, a framework (illustrated in Figure 2.1) has been developed by which the climate change factors are translated into potential loadings, and from that deterioration processes and consequences.

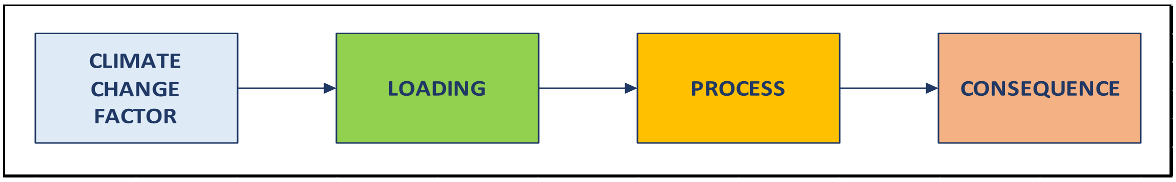


Figure 2.1 Translation from climate change factor to consequence

This has been adopted for developing relationships that can help to qualitatively and quantitatively establish how climate change will affect deterioration of an asset, where the key areas of vulnerability lie, and what the impact of that might be. It provides transparency, with the contributing factors for any consequence upon the asset readily traceable.

The conversion of each climate change factor into loadings is illustrated in Appendix B, and described below.

2.3.3 Different environments

FCERM assets sit within three distinct environments, which we have labelled as ‘Coastal’, ‘Fluvial’ and ‘Estuary’ (the latter capturing tidal river reaches too).

Coastal

Coastal is open coast (i.e. the sea, and saltwater), and the following climate change factors have to be considered:

- Sea Level Rise
- Storm Surge
- Wave Climate

These can result in a series of changes to asset loading conditions, defined as: increase in peak water levels; changes in hydrostatic pressure distributions; changes in areas wetting and drying; increase in direct wave impact forces; changes to indirect wave loading; and increases in wave velocities.

Sea level rise will have a constant (day-to-day) impact upon assets, which in itself can have a day-to-day impact upon the size of waves reaching the shoreline. However, storm surges, and wave height increases are impacts which are only accounted for in extreme events (i.e. storms).

Fluvial

This is defined as a river (i.e. a channel, and freshwater, with no tidal influence), and, in the context of the climate change factors being considered here, only the following applies:

- Fluvial Flows

The changes in asset loading conditions as a result of this have been identified as: increase in peak water levels; changes in hydrostatic pressure distributions; changes in areas wetting and drying; increase in water volume; and increases in flow velocities.

Fluvial flow increases will not have a constant (day-to-day) impact but would have a regular impact, that is, coincident with any periods of higher rainfall.

Estuary

Between the river and the sea lie the tidally influenced areas referred to variously but including 'Estuary' and 'Tidal River'. For the purposes of this project, they have been collectively referred to as Estuary, albeit noting below that some differences in the dominant influences will occur within these water bodies.

Estuary

An estuary can often take the form of a large (wider) water body, that is not river channel, primarily saltwater dominated. The following climate change factors therefore need to be considered:

- Sea Level Rise
- Storm Surge
- Fluvial Flows (maybe)

The effects on asset loading conditions would be: increase in peak water levels; changes in hydrostatic pressure distributions; changes in areas wetting and drying.

It is possible that increases in river flows could have a small influence here, but in the context of this study it is assumed that those might be dissipated to a large extent once the wider estuary is reached, and it is also assumed that within the larger water body of an estuary any changes in water volume would not be significant in terms of raising water levels.

Sea level rise will have a constant (day-to-day) impact upon assets. Increased water levels due to storm surges would be a factor in extreme events (i.e. storms). If river flow increases are of consequence for an asset in an estuary environment, this would not be a constant (day-to-day) issue, but would be a regular (several times per year) occurrence.

Note that the estuary water body will generally be sheltered from ocean waves, so the impacts of changes in wave climate are likely to be slight. There will, though, be wave action to take into account in terms of loading on assets, but that will be from locally generated waves not the offshore wave climate. Within estuaries these waves are generally fetch limited, not depth limited, and therefore would not be significantly affected as a consequence of changes in water levels; the main difference would be that waves of similar height to present would impact upon assets at a higher elevation.

Tidal River

Where an estuary narrows (i.e. it becomes a channel but where tidal waters can reach), this is also sometimes referred to as tidal river. This too will have saltwater intrusion but will be primarily freshwater dominated. In those settings, the following climate change factors need to be considered:

- Sea Level Rise
- Storm Surge
- Fluvial Flows

Within a tidal river there is assumed to be no wave activity, but assets here will be affected by sea level rise and storm surges increasing water levels. The effects on asset loading conditions would therefore include: increase in peak water levels; changes in hydrostatic pressure distributions; changes in areas wetting and drying; increase in water volume; and increase in flow velocities.

Sea level rise will have a constant (day-to-day) impact upon assets while increased water levels due to storm surges would be a factor in extreme events (i.e. storms). But both of these will have a diminishing effect moving upstream. If river flow increases are of consequence for an asset in an estuary environment, this would not be a constant (day-to-day) issue, but would be a regular (several times per year) occurrence.

2.3.4 Additional climate change factors

The above hydrodynamic factors are by no means an exhaustive list of all the climate parameters that could possibly change in the future, and which could impact FCERM assets. Other factors include:

- Wind
- Storm Frequency and Sequencing
- Rainfall (other than increasing fluvial flows)
- Temperature

These have not, however, been included within the primary assessments carried out in this project because either:

1. The climate change research into these factors is not yet sufficiently developed and still to provide guidance on the direction and magnitude of changes for use in analysis.

   or,

2. Within the bounds of this study the magnitude of change in those factors as a result of climate change is not expected to have a significant effect on most of the assets being considered here.

Although these other factors are not primary considerations for this study at this time, as climate change science develops it may become appropriate to add them into future iterations of FCERM asset vulnerability.

Nonetheless, identifying where and how these might impact upon those assets being considered by this study could be valuable to inform future considerations. Therefore, where it is considered that any of these additional climate change factors could have a potential impact of any significance, this has been identified as part of the deterioration processes assessment. For those asset types where it was considered that these effects should be considered further, then an additional assessment of vulnerability has been undertaken.

Wind Direction and Speed

Changes in dominant wind direction (and speed) is a variable that could impact beach sediment movement and thus the performance of this asset and beach control structures. It will also have an influence on local wave conditions and could, through causing more damage such as fallen trees and debris entering watercourses, have an impact upon the management of fluvial assets. However, there is limited available research on the effects upon this as a result of climate change, which would also be highly site specific.

Storm Frequency and Sequencing

Storm frequency and tracks are important contributors to extreme storm surge values and potential impacts, but there is currently little clear scientific research upon which to quantify any change. The potential for increased frequency of storms and hence a second storm impacting an already damaged asset (sequencing) is now being identified as a potential factor to consider in the future. However, there is as yet little relevant research on the probabilities of storm sets becoming more frequent, so this knowledge needs to be developed before it can be applied.

Rainfall

A key consequence of rainfall changes for FCERM planning will be impacts on river flows (a primary consideration for this study). However, there will be other ways in which changes in rainfall may affect deterioration of various assets, such as longer periods of drought or increased levels of saturation.

The UKCP09 climate scenarios (see http://ukclimateprojections.metoffice.gov.uk/) provide sound projections of rainfall characteristics such as seasonal and annual patterns and rainfall over 24-hour periods. However, detailed projections of local-scale high intensity rainfall events, the events that are of increasing interest to flood risk management, remain poorly resolved in existing climate models and thus information on potential changes to them are more uncertain.

Temperature

A small change in temperature is considered unlikely to have a significant impact on the deterioration of most assets, with very few FCERM assets likely to be notably affected by predicted changes of 1º or 2ºC. There will be exceptions to this, but this is currently less likely to be an issue than other factors being considered.

Loadings

For the four ‘additional’ climate change factors included in this appraisal, the initial stage in identifying potential deterioration processes was the definition of seven changes in ‘loading’ conditions that could directly impact FCERM assets. These are: change in wind speed and/or direction; change in wave direction and/or size; reduction in recovery time between storms; increased freshwater flows; increased winter ground saturation; increased summer ground desiccation; changes in vegetation; and changes in fauna.

2.3.5 Summary

In summary, the climate change factors considered for each environment are as shown in Tables 2.4 and 2.5.

Table 2.4 Climate change factors considered for each environment

<table>
<tr><th></th><th>Sea Level Rise</th><th>Storm Surge Increase</th><th>Wave Height Increase</th><th>Higher Peak River Flows</th></tr>
<tr><td>Coastal</td><td>YES</td><td>YES</td><td>YES</td><td>no</td></tr>
<tr><td>Estuary</td><td rowspan="2">YES</td><td rowspan="2">YES</td><td>(local waves)</td><td>(limited)</td></tr>
<tr><td>(Tidal River)</td><td>no</td><td>YES</td></tr>
<tr><td>Fluvial</td><td>no</td><td>no</td><td>no</td><td>YES</td></tr>
</table>

In addition, the following have been considered for assets where the potential for vulnerability has been identified:

Table 2.5 Additional climate change factors considered for each environment

<table>
<tr><th></th><th>Wind</th><th>Storm Frequency</th><th>Rainfall</th><th>Temperature</th></tr>
<tr><td>Coastal</td><td rowspan="2">YES</td><td>YES</td><td rowspan="3">YES</td><td rowspan="3">YES</td></tr>
<tr><td>Estuary</td><td>no</td></tr>
<tr><td>Fluvial</td><td>no</td><td>no</td></tr>
</table>

3 Asset assessment

3.1 Introduction

A range of studies have been carried out as part of this project to investigate the potential impact that climate change may have upon FCERM assets. The purposes of these studies were to better understand the nature of deterioration for those assets and how vulnerable they might be to different climate change factors. The details of these studies are presented in Appendices A, B and C. An overview of each of these pieces of work is described below, with the outcomes presented and discussed in Section 4.

The knowledge and information generated by this work could then be used at a future point in time to gain an appreciation at a national level of the overall implications that climate change could have in terms of the extent of problems arising from increased deterioration, the costs of dealing with that, and where the priorities lie in the future. Section 5 and Appendix D discuss this in more detail.

3.2 Material degradation

Material degradation is only one component of asset deterioration; however, the potential for this to be affected by climate change is an important consideration.

Research into existing literature was undertaken to determine the current state of knowledge with respect to existing rates of degradation. The results of the literature search, presented in Appendix A, are given in two parts:

- Information on degradation processes.
- Information on degradation rates.

Any information that could be sourced on the latter is summarised for Concrete, Structural Steel, Rock and Timber; information on the former also includes Blockwork/Masonry, Asphalt and Sealants.

This assessment could not be climate change specific, as that knowledge does not yet exist, but the information contained therein will help provide understanding and context when it comes to considering these issues in the future, and particularly perhaps when considering any 'futureproofing' design of FCERM assets.

3.3 Asset deterioration assessments

3.3.1 Influence of climate change on deterioration mechanisms

The core output from this study is the development of relationships between climate change factors and deterioration processes for the different asset types, from which assessments of vulnerability and impacts can be established. These provide a valuable point of reference for practitioners to better understand the deterioration mechanism specific to each asset type and why climate change may or may not be an issue that requires consideration.

Having identified the deterioration processes that would be susceptible to the effects of climate change, the focus of this work has then been on carrying out a qualitative assessment of the vulnerability for each asset type.

In developing the qualitative approach for this study, matters such as variability in asset type and in asset setting have been taken into account. For example, an outfall might be made of concrete, metal or plastic, each of which will have different deterioration characteristics; a wall in a fluvial setting will experience different deterioration processes to one in a coastal setting; susceptibility to certain deterioration mechanisms may be different if a channel bed or foreshore is sand, silt or gravel. This results in the initial list of 47 FCERM asset types being expanded to 80 separate assessments (with further subdivision within those where possible). This remains a very high-level definition of those asset types and does not cover all possible combinations of construction form and setting for which there would be several hundred permutations. But with this, the ability to define deterioration processes and determine the potential vulnerability of those asset types from climate change has been improved considerably. These assessments are all presented in Appendix B.

The quantitative assessments also enable a relative categorisation of the potential vulnerability of each asset. From this, it is possible to prioritise which assets are likely to be most vulnerable to climate change, and to screen out those that are of less concern and do not warrant more thorough analysis at this time.

3.3.2 Categorisation

In developing the approach to be adopted, it was concluded that the vulnerability of an asset to the effects of climate change upon its deterioration would, at a qualitative level, be described as either 'High', 'Moderate', 'Low' or 'Negligible'. In order to do that, consideration also needed to be given to its impact upon those assets, and the approach taken was to relate the level of additional effort that could be required to maintain that asset. In order to provide consistency in conclusions, the following definitions were used:

'HIGH'	Change could result in *a* **significant (large or rapid) increase** *in maintenance commitment and/or chance of failure* due to deterioration
'MODERATE'	Change likely to result in *a* **notable increase** *in maintenance requirements or repair/replacement of elements* due to deterioration but without significantly increasing failure probability
'LOW'	Impacts *may result in* **some small increases** *to the level of maintenance* due to deterioration, e.g. the potential for some increase in the frequency of routine activities
'NEGLIGIBLE'	The impact of climate change factors on deterioration will result in **little if any change** *to the maintenance* of the asset

3.3.3 Assessment reporting template

To achieve consistency in capturing and relaying the outputs from the assessments, a template was developed for use (Figure 3.1). Embedded within this are deterioration process diagrams, showing the relationships between the climate change factors and effects on deterioration. This also presents the nature of activities that may be required to address this change in deterioration, and thus conclude the relative potential impact upon that asset type.

ASSET TYPE: e.g. Vertical Seawall	ENVIRONMENT: e.g. Coastal

DESCRIPTION

DEFINITION IN CAMC:

Quote the description used in CAMC for this asset type

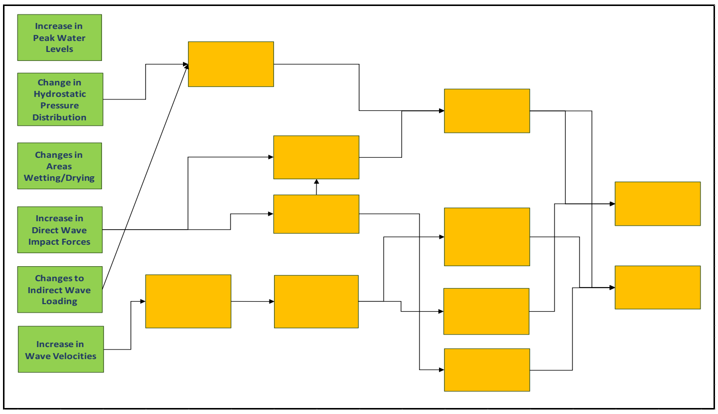
Add to above description. Discuss variations etc. (form, type, setting etc.) or other general notes relevant to the subsequent assessment

CLIMATE CHANGE FACTORS CONSIDERED				
Sea Level Rise	Storm Surge	Wave Height	River Flows	Other
Yes/No	Yes/No	Yes/No	Yes/No	Yes/No

Anything to note on 'other' climate change factors considered

RELATIONSHIP BETWEEN DETERIORATION PROCESSES AND CLIMATE CHANGE FACTORS

Mapping of deterioration processes and climate change influences on those.



QUALITATIVE ASSESSMENT

Description of key aspects of climate change impacts on deterioration of the asset

What does this mean for increased maintenance/repairs etc.?

Provide supporting information for qualitative magnitude of impact

MAGNITUDE:			
HIGH	MODERATE	LOW	NEGLIGIBLE
?	?	?	?

OTHER POTENTIAL IMPACTS

Performance related impacts/issues (as above text should relate to deterioration only)

Comment on systems/wider effects (as above text should relate to the asset only)

Figure 3.1 Asset deterioration assessment reporting template

3.3.4 Other potential impacts

As defined earlier, this study focuses on deterioration only and not assessing effects of climate change upon the standard of protection provided by defences, or other performance related metrics. However, where there is potential for climate change to impact upon performance or other assets, that possibility has been identified within the reporting template alongside the qualitative assessments, as this output may be useful for practitioners to appreciate how these same climate change factors may affect other aspects of the asset, or have a knock-on effect upon other adjacent or downstream assets.

3.3.5 Additional climate change factors

The qualitative assessments focused primarily on the potential changes in asset deterioration from climate change induced effects upon hydrodynamic factors. However, when undertaking the qualitative assessment of deterioration processes, consideration was also given to whether any other climate change factors could also potentially alter the vulnerability of that asset type.

For each of these asset types where a notable deterioration effect was identified, additional assessments were carried out. A further deterioration process diagram has been produced, together with a brief summary of that impact, as a supplement to the primary assessments. These are also contained in Appendix B.

3.4 Quantification of vulnerability

3.4.1 Methods

Outputs arising from qualitative assessment are essentially an expert opinion on the degree of impact. Expert judgement, such as used in condition characterisation, forms an important element of risk assessment; however, it is rarely precise and not quantitative. Although it might be possible to determine whether some asset types are broadly more susceptible to climate change than others, the form and setting of the asset is a fundamental consideration in any assessment of vulnerability and magnitude. Many structures with otherwise very similar characteristics could have quite different vulnerability due to their geometric properties and level of exposure. To not quantify and assess the influence of those differences therefore constrains the quality and robustness of conclusions from a generic assessment of vulnerability based just on broad asset type. Simply put, to provide any conclusions on the overall impacts of climate change upon assets, some quantification is likely to be required.

There are a range of levels and associated techniques at which an assessment of impacts might be performed, with varying levels of complexity and data requirements. In Appendix C, those methods that begin to better quantify (either numerically or comparatively) the climate change impacts on asset deterioration have been explored.

Initial assessment is made for individual assets of the potential to perform any quantified assessment of deterioration, and the types of methods that might be available and suitable to employ. Areas of commonality between different asset types are also identified, which may be the most appropriate approach to consider for any national-scale assessments.

3.4.2 Illustrative examples

A set of illustrations are also included in Appendix C, providing examples of how the effects of climate change upon certain deterioration mechanisms can be quantified. For example, they show how an increase in flow speed or water level might modify the result of a calculation into damage or protection requirement. These are not necessarily the definitive formulae for design of assets, but selected to simply demonstrate to the reader how effects can be accounted for, and therefore may result in a change in requirements for the maintenance, repair or upgrading of particular asset types.

A template used to present these details has also been developed (Figure 3.2).

PROCESS: *Mechanism being illustrated*
DESCRIPTION: *Detail on the mechanism and how climate change may affect that*
APPLIES TO: *Asset type(s) for which this mechanism is applicable*
BASIC EQUATION: *Formula and description of parameters* *Sketch/Figure (if relevant)*
WORKED EXAMPLE:
BASECASE: *Assumptions for parameters used in the example calculation* *Illustration of the calculation with those parameters*
CLIMATE CHANGE IMPACT: *Assumptions for climate change and how that alters those parameters* *Illustration of the calculation with those differences in parameters highlighted*
COMMENT: *Summary of how, in this example, the extent to which climate change alters the result, and what the implications of that might be for any increased activity such as maintenance or repair*

Figure 3.2 Quantitative assessment illustration template

4 Assessment outcomes

4.1 Material degradation

Although material degradation will be a factor contributing to the deterioration of an asset, the change in the rate of material degradation purely as a consequence of climate change is usually going to be relatively low compared to other environmental and physical factors, including the context in which that construction material has been utilised.

The more significant issue is the potential for deterioration of the asset as a whole, for example destabilising or damaging structural elements and reduction of structural integrity. These are also most likely to be impacts observed over shorter timescales (as a consequence of climate change), when compared to material degradation (which will be a slower and more gradual process).

Notwithstanding that, literature has been reviewed to determine the nature of degradation processes for some of the more commonly used material types, how they influence the rate of degradation, and how the rate might be affected by climate change. This is presented in Appendix A, and the conclusions of that are outlined in the sections below.

4.1.1 Concrete

One of the major threats to the longevity of concrete structures is carbonation, which occurs when atmospheric CO_2 penetrates into the structure to expose steel reinforcements to corrosion. Corrosion caused by chloride penetration is another serious threat to concrete durability causing cracking, delamination or spalling.

Both corrosion mechanisms can be affected directly and indirectly by climate change such as increasing concentrations of atmospheric CO_2, rising air temperatures and sea level rise, but the time it will take for climate change to exacerbate carbonation and chloride-induced corrosion of concrete structures will depend on their location and level of exposure to the elements. One difference that may result from climate change will be the change in exposure zones, particularly for coastal structures, which could accelerate or decelerate material degradation due to changes in wetting/drying at particular points on the structure.

The base rate of any degradation, and thus change in that due to climate change, is also highly dependent upon the nature of the concrete mix design and its construction, which is going to be asset specific. The same conclusion is reached for potential abrasion of concrete, which is further dictated by the nature of the abrasive material and the level of exposure of the asset.

In summary, however, there are no typical degradation rates for concrete published at present. The rate of material degradation without climate change is unpredictable due to the range of controlling influences, and therefore predicting a generic change in the rate of material degradation due to climate change influences is also not possible.

4.1.2 Structural steel

Corrosion rate distribution and aggressiveness upon structural steel can vary considerably, depending upon the location and conditions prevailing at the location of the structure. This is particularly apparent in sea water, where conditions are highly variable across different elevations, but may also depend upon the presence of microbiological organisms, soil conditions and measures taken to protect the structure.

With such variability in the present-day base rates, predicting the effects of climate change upon the material degradation is impossible; quoted mean rates vary by a factor of 2 to 3 and the upper limit rates can be several times greater. Consequently, the change in rate occurring for any given structure may still fall within the upper bounds, or even typical ranges quoted, and may only really be estimated at an asset-specific level with base data for that particular asset.

Even though it may not be readily quantified, steel degradation is likely to be affected directly by climate change such as rising air temperatures, changes in humidity and sea level rise, as the chemical reactions tend to increase with increased temperature and exposure to more humid conditions.

One factor that could affect a change in corrosion rate, particularly for coastal assets, may be the change in exposure zones due to sea level rise. This could affect (accelerate or decelerate) steel degradation due to changed zones of wetting/drying. Similar changes may occur in fluvial settings with increases in river flows altering the exposure of the steel to air and water, or affecting groundwater conditions in the soil.

Another factor is the potential for abrasion of steel. This will occur due to the movement of sediments on a beach or within a river channel. Changes in climate which lead to more aggressive conditions, for example faster flows or larger waves resulting in greater mobility of the sediments, will therefore have an impact upon the rate with which that occurs.

Although it is currently difficult to quantify the effects of climate change on structural steel corrosion, it is obvious that for future planning purposes there is benefit to be obtained in assessing the magnitudes and uncertainties associated with corrosion estimates related to the use of climate change projection models.

4.1.3 Rock/stone

Rock degradation is, by its nature, inexact and difficult to judge. Differences in rock type (e.g. granite or limestone), and even the characteristics of individual rocks within the same rock type, make any attempt to define typical rates of degradation meaningless. It therefore also follows that changes in those rates due to climate change cannot be generically estimated.

On the assumption that a reasonable quality of rock has been used for construction, then there will generally be little effect from weathering, dissolution or freeze–thaw in a UK climate, either now or with climate change.

The impact of climate change upon the rate of degradation of rock used in construction is most likely to result from more aggressive conditions (waves or flows) resulting in more movement of pieces and thus increasing the potential for wear and breakage. Even then, the potential for this cannot be generically stated and our ability to distinguish the consequences is still constrained by poor understanding of the mechanisms, their relationships to environmental controls and the lack of long, reliable deterioration records.

4.1.4 Timber

Timber degradation can be affected directly and indirectly by climate change through changes in water levels altering the exposure to wetting and drying, resulting in greater decay (rotting); changing temperatures that may alter the levels of marine borers found in the water; or larger waves/greater flows, which may change the dynamic regime and thus produce more aggressive and abrasive conditions. No doubt, climate change will increase these rates, but the rates are also highly dependent upon the local environment, for example the presence and nature of any abrasive material.

Attributing values to the impact upon degradation resulting from climate change is difficult to determine, as baseline rates for present-day conditions are not generically identifiable. This is further complicated by considerable variability in the resistance of timber species to different degradation processes: some timbers are more resistant to one process (e.g. marine borers) but less to another (e.g. abrasion), while others have the opposite characteristics. Consequently, the rate of degradation is not only critically dependent upon the timber type used for a specific asset, but also upon which degradation process is dominant and the actual nature of the climate change, that is, whether that results in more aggressive hydrodynamic conditions or a change in water temperature.

4.1.5 Other materials

It is even more difficult to establish degradation rates for Blockwork/Masonry, Asphalt or Sealants. However, this is considered to be less important, for the following reasons:

Blockwork/Masonry:	The degradation of such materials will be similar to that of their constituent parts (e.g. where the properties are similar to those of concrete).
Asphalt:	The design life of asphalt is relatively low (c. 25 years) and degradation of its component parts is unlikely to be significantly affected by climate change over that period.
Sealants:	Again, sealants have a relatively short design life and degradation is unlikely to be significantly affected by climate change over that period. Sealants can easily be changed as a maintenance operation.

Other materials used in construction, such as plastics, glass, ceramics and geotextiles may also be vulnerable to changes in climate, but information on those is limited and in many cases the reasons outlined above would again apply.

Consequently, this study has not investigated rates for any of these further.

4.2 Deterioration processes

The qualitative assessments in Appendix B provide an asset-by-asset appraisal of the deterioration processes and how climate change may impact upon those. From that, and in that context, the assets most likely to be vulnerable to climate change and the main factors driving that have been established. The following subsections summarise the outcomes of these assessments.

4.2.1 Fluvial

In the case of fluvial assets, a general conclusion drawn from the qualitative assessments is that the impacts of climate change upon capacity and performance are likely to require some upgrade to the assets well in advance of any significant impacts from deterioration due to climate change. For example, it is probable that outfalls and culverts will need to be replaced due to being of inadequate size to convey higher flows sooner than the point at which those higher flows and associated effects will have increased deterioration to an extent requiring a notable increase in maintenance or replacement. Similarly, the potential for out-of-bank flows from open channels and over embankments as a result of higher flows and peak water levels is likely to result in a need for improvement ahead of greater deterioration becoming a significant factor.

In general terms, the degradation of the materials used for construction of these assets, such as concrete and steel, are not likely to be directly affected by climate change, with the primary cause of any material degradation more likely to come indirectly from higher rates of abrasion (e.g. from more sands and gravels being washed through the watercourses as a consequence of those higher flows). Another possibility is higher debris flows within the watercourses leading to greater impact damage. Neither are, however, considered to be of any notable significance for most assets, although one construction material type which does feature in a few instances as having higher potential vulnerability to climate change effects is masonry, with the mortared joints being an area of possible susceptibility.

The situation is a little different for assets with moving parts, where increased frequency of operation (e.g. due to higher risks of flooding) could lead to greater wear and tear on those elements, with faster degradation of seals etc. unless there is an increased maintenance commitment. However, this impact is still expected to be fairly modest by comparison to the aforementioned performance/capacity issue.

For some asset types there is a more notable link between climate change and deterioration. One example is the higher potential for erosion and displacement of the protective covering on embankments and river banks as a result of higher flows, particularly where these are constructed of lighter materials such as certain permeable linings. Likewise, scour or erosion to unprotected (turfed) surfaces is another area where climate change could result in a need for more maintenance, repair or even replacement. In such cases, geotechnical instability may also increase due to higher water levels on the river side of these structures.

One of the most common potential impacts upon fluvial assets is that of river bed (or bank) erosion as a result of higher flows, leading to the potential for scour and undermining of the assets. This applies to a number of different asset types and will depend upon the nature of the watercourse (i.e. its size and materials, the magnitude of the increased flows and the nature of design of the asset).

Based upon the qualitative assessments, the impacts of climate change upon deterioration are assessed to be High or Moderate for only one-third of fluvial asset types.

4.2.2 Coastal

The vulnerabilities of assets in a coastal environment are somewhat different from those in a fluvial setting. This results from the much more dynamic conditions that are experienced on the open coast by comparison and the strong inter-relationships between the water levels, waves and local morphology that is regularly reshaped by these. Therefore, even modest changes in those conditions as a result of climate change can have a significant impact. This also creates a more aggressive situation in terms of abrasive and corrosive conditions resulting from the movement of beach materials, in addition to the saltwater presence.

Greater material degradation due to higher rates of abrasion of concrete, timber and steel, and corrosion (of steel piling or reinforcement), will be a factor for most coastal assets. This results predominantly from the increased mobility of beach materials, and in particular shingle, being constantly moved around by waves. This is not, however, the most common or significant impact. Almost all coastal assets are vulnerable to instability created by beach lowering and scour. This is likely to be a more widespread and substantial issue with higher water levels resulting in higher waves further inshore, leading to greater beach drawdown and movement. In addition, this greater beach drawdown will result in yet larger storm waves reaching the asset at the back of the beach, further exacerbating this problem.

These same factors also result in greater direct wave forces upon the assets. This would increase the potential for destabilising assets, for example removing protective cover layers to revetments, uplift upon timber slipways or steps, overturning forces on groynes. It could create higher dynamic loading such as internal water pressures resulting in displacement or settlement of fill. It will also lead to greater erosive forces, such as on cliffs or dunes, or for example at joints between blocks or sections of wall.

Another impact for some coastal assets will be the higher water levels and waves resulting in greater rates of overtopping. This can lead to more damage to/deterioration of the landward side of the asset (e.g. an embankment slope or promenade), or lead to greater water ingress and potential instability or loss of retained fill, compromising the asset or what it is protecting.

All of the above are also key considerations for any performance-related impacts of climate change.

By contrast with the fluvial assets (Section 4.2.1), the impacts of climate change upon deterioration have been qualitatively assessed to be High or Moderate for two-thirds of coastal asset types.

4.2.3 Estuary

Assets set in an estuary or tidal river environment unsurprisingly experience some similar effects on deterioration to those in fluvial rivers or on the open coast. Conditions are less extreme than the open coast but some factors such as sea level rise still have an impact, while higher flows from rivers can also be a factor. So, assets in an estuary can experience a different combination of influences. Consequently, some impacts will be higher and some lower than experienced in those different environments.

A key determining factor in many cases will be where the asset is located. Impacts in an open estuary and impacts in a tidal river can be different for the same asset type.

Within estuaries, climate change has been qualitatively assessed to have High or Moderate impact upon deterioration of approximately half of the asset types.

4.2.4 Additional climate change factors

A total of 12 of the original 47 asset types were identified as being potentially vulnerable to deterioration from additional climate change factors. A high proportion of these are either natural assets, or asset types that have a softer element to them, such as turfed embankments and unprotected river banks.

As natural features, created and defined by the processes that form them, certain asset types are going to be inherently vulnerable to any climate changes that alter those processes. Changes in wind patterns are a potential issue for natural coastal features, such as beaches and dunes, with an alteration in the incident forces that drive their behaviour resulting in greater erosion. Likewise, changes in storm frequency, and in particular storm sequencing, could reduce the potential for beaches to recover, with that also producing the increased potential for impacts upon other coastal assets that these features help to protect. The spatial variability in conditions do though mean that the likelihood and magnitude of such impacts are going to be entirely location specific and impossible to quantify generically.

Changes in rainfall are also identified as having the potential to affect several asset types through, for example, leading to potential for reduced structural stability of embankments and river banks due to greater saturation, or in the case of drought the potential for fissuring. Higher rainfall may also mean greater frequency of operation to control flood waters, such as penstocks or pumping stations, leading to increased wear and tear.

Temperature change, plus changes in rainfall, have the potential to lead to differences in flora and fauna, requiring additional maintenance to clear or control to prevent weakening of assets such as embankments through burrowing or root systems. A change in temperature could also result in a change in the activity of marine borers, a potential issue for timber structures at the coast.

Although not included within these assessments, there could be other impacts from climate change that indirectly impact upon FCERM assets, or flood and erosion risk management itself. For example, wind-related climate change effects on fluvial assets may include trees being blown over and increased blockages within watercourses; or power outages that effect the operation of equipment. Impacts are also not always negative. Potential opportunities/positives of climate change may for example result in higher winter temperatures with a reduced need for/amount of salt spreading, which reduces the salt corrosion of steel in assets.

The assessments of these additional factors conclude, however, that none of these additional factors increase the vulnerability of these particular assets over and above that concluded for the primary hydrodynamic factors. In the case of cliffs, it is only a proportion with particular geology where this vulnerability may increase as a result of rainfall-induced landslip. It is also debatable whether this is indeed an increase in 'deterioration' of that asset. These are by definition an erodible edge to a piece of land and that deterioration or failure can only therefore really be defined as their erosion, which might also be considered to be a measure of their performance.

In summary, the primary (hydrodynamic) climate change effects are likely to be the dominant cause of any change in deterioration for most assets where that change is sufficiently notable that a need to respond is identifiable as Moderate or High.

4.2.5 Qualitative assessment summary

In all, 80 different combinations of asset type and setting have been assessed. In each case, the relative vulnerability has been categorised as 'High', 'Moderate', 'Low' or 'Negligible', based upon the descriptions presented in Section 3.3.2. The summary of these assessments is presented in Table 4.1.

This information has been used to prioritise those assets where most attention ought to be focused, and to screen for those for which it would be most appropriate to develop advanced methods for quantified assessment of potential impacts.

Table 4.1 Qualitative assessment summary

	ASSET TYPE		COAST	FLUVIAL	ESTUARY
1.1	Open Channel			*Negligible*	
1.2	Simple Culvert			LOW	LOW
1.3	Complex Culvert			LOW	
2.1	Bridge			LOW	
2.2	Utility Services			LOW	
3.1	Embankment	Revetment	HIGH		HIGH
		Turfed - Unprotected		HIGH	HIGH
		Permeable Revetment		MODERATE	
		Impermeable Revetment		MODERATE	
3.2	Wall	Vertical Seawall	HIGH		MODERATE
		Revetment Type	HIGH		
		Raised River Wall		MODERATE	
3.3	Flood Gate		MODERATE	LOW	LOW
3.4	Demountable		MODERATE	LOW	LOW
3.5	Bridge Abutment			LOW	
3.6	High ground	Natural		LOW	
		Lined - Permable		MODERATE	
		Linded - Impermeable		MODERATE	
3.7	Quay				LOW
3.8	Beach		HIGH		
3.9	Dunes		MODERATE		
3.10	Barrier Beach		HIGH		
3.11	Promenade		LOW		
3.12	Cliff	Unprotected	MODERATE		
		Stabilised Slope	LOW		
4.1	Saltmarsh				HIGH
4.2	Mudflats				LOW
4.3	Washland			*Negligible*	
5.1	Screen			*Negligible*	
5.2	In Channel Stop-logs			*Negligible*	
5.3	Control Gate	Mitre Gate		MODERATE	MODERATE
		Radial Gate		LOW	
		Rising Sector Gate		LOW	LOW
		Guillotine Gate		LOW	
		Penstock		LOW	
5.4	Outfall		MODERATE	LOW	LOW
5.5	Weir			MODERATE	MODERATE
5.6	Spillway			MODERATE	
5.7	Stilling Basin			LOW	
5.8	Draw-off Tower			*Negligible*	
5.9	Fish Pass			LOW	
5.10	Hydrobrake			LOW	
5.11	Inspection Chamber			*Negligible*	
5.12	Jetty			MODERATE	MODERATE
6.1	Groyne	Timber	MODERATE		
		Rock	LOW		
6.2	Breakwater		LOW		
6.3	Slipway	Concrete	MODERATE		
		Timber	MODERATE		
6.4	Steps		MODERATE		
6.5	Ramp		MODERATE		
7.1	Instruments - Active Monitoring			*Negligible*	
7.2	Instruments - Passive Monitoring			*Negligible*	
8.1	Beacon		LOW	LOW	MODERATE
8.2	Buoy		*Negligible*		
8.3	Signal		*Negligible*		*Negligible*
8.4	Signage				*Negligible*
8.5	Dolphin				LOW
9.1	Pump House			MODERATE	MODERATE
10.1	Abutment			*Negligible*	
10.2	Central Pier			*Negligible*	

4.3 Quantifying vulnerability

4.3.1 Overview

The quantification of the effects of climate change upon the deterioration of any asset is not straightforward. Any reduction in the physical condition of the asset is multi-faceted; each component element of a structure is subjected to different mechanisms, and will have variable resistance to the processes acting upon it. The task is further complicated by the lack of any existing baseline of current deterioration against which to measure the differences that may result in that baseline as a result of climate change.

The general appraisal of quantification methods (Appendix C2) indicates that the most appropriate approaches to measure deterioration will be through application, and perhaps adaptation, of existing design formulae; enabling the calculation of requirements with and without climate change included for within the hydrodynamic parameters. However, it is also concluded that for several asset types or deterioration mechanisms there are no simple and easily applied methods to quantify change, and where such methods do exist they will in many instances require considerable (design-level) data to be applied.

Notwithstanding that, there are some areas of commonality between several asset types with respect to some of the deterioration mechanisms. Examples of this include the effects of beach scour on many coastal assets; similarly, channel scour on many fluvial assets. These have been identified through review of each of the individual qualitative assessments to capture the key deterioration processes for each. These present a means to potentially simplify the approach to quantifying impacts upon asset deterioration at a broader scale as they might also be aligned to making best use of nationally available datasets and negate the need for bespoke and asset-specific analysis to obtain a general picture of total impacts.

Although the application of a national-level assessment is outside the scope of this project, the high-level appraisal of these methods is valuable to present some concepts and outline for their further development.

4.3.2 Potential magnitude

Illustrative examples are presented in Appendix C.3 primarily to show how a change in hydrodynamic parameter arising from climate change can alter the vulnerability of an asset and thus the impacts upon actions required to address that. These provide practitioners with some useful insight into how to account for the effects of climate change in their future assessments. The examples also provide some initial insights into the range of impacts that climate change might have upon particular asset types and deterioration mechanisms.

Although only example values have been used for the calculations in the illustrations, these show some quite sizeable differences in potential impacts. For example, a 20cm increase in sea level rise in the example shown for toe scour results in a 14% increase in scour depth, whereas that same increase in sea level results in a doubling in the area of damage to a cover layer and a four-fold increase in overtopping rate. It must be stressed that these are by no means directly comparable in terms of suggesting that overtopping and cover layer stability are many times more significant than toe scour, but it does demonstrate that, depending upon the characteristics of the asset and the nature of the deterioration process of concern, a wide variation in conclusions can result.

In some cases, the change in deterioration may not require a corresponding incremental increase in activity but a need to change completely from one approach or system to another; for example, a protective cover layer of certain type needs to be replaced by a more robust form of protection, or the need to provide anti-erosion measures where there was no need before. Conversely, there will be examples where the increase in flows or energy resulting from the change in climate change factor does not actually require any additional action due to the nature of the design in place already. Examples of that may include where standard sizes are used and the change in conditions do not mean that the design thresholds for that are yet exceeded; for example, particular revetment blocks which come in standard thicknesses, or proprietary flood gates or demountables that are manufactured as part of a product range.

What the illustrative examples begin to demonstrate is the non-linear nature of the relationship between climate change and asset vulnerability; that is, there is no generic direct correlation between a percentage change in hydrodynamic condition and the change in damage/response required; it varies depending upon the deterioration mechanism that is most affected. Furthermore, if a range of different characteristics were selected, then no doubt results would be different yet again.

The conclusion to be drawn therefore is that in considering the impact of climate change upon deterioration, some level of asset-specific quantification using at the very least some basic parameters is necessary. That would include basic information on asset dimensions/configuration and local hydrodynamic conditions as a minimum. Ideally, these would be supplemented with information on setting (e.g. nature of the channel or beach form and material) and details on some of the key component elements of the asset (e.g. materials and size).

4.3.3 Developing and applying the quantification of deterioration

In terms of national application, the question will be how to utilise this type of information to quantify total potential impacts of climate change and produce tools that could be used widely.

The considerable variability in magnitude of impacts that can be seen from the illustrative examples suggests that, although broad-brush methods are required, approaches need to be able to take some account of the characteristics of the asset. For that reason, any generic probabilistic approaches or high-level deterioration curves are unlikely to be adequate to represent change in deterioration in a way that the quantification of impacts can be considered with confidence to be reliable.

Due to the limitations on the data that is likely to be available, any quantification of deterioration is expected to require some form of hybrid approach; for example, mixing some quantifiable information such as structure geometry with some non-dimensional data such as bed material type. This would enable rule bases to be generated to calculate potential changes in deterioration for individual assets in a way that can also be codified to allow application at a national level.

An extension of that is to create look-up tables for which values for a series of different combinations across a range of typical conditions can be calculated, against which individual assets can be compared and the results of the change in condition identified. Simple quantifiable methods, along the lines of some of those presented as illustrative examples in this study, will be of a suitable level to inform the development of such tables.

5 Establishing impacts

5.1 Introduction

Developing and applying the methods for better evaluating the effects of climate change upon deterioration for each asset type helps to improve understanding and awareness, and to determine measures to deal with that deterioration. However, to have some indication of what that might mean at a national level also requires an appreciation of the total number of those assets that would be affected and the consequences of that, which can be expressed as:

Total impact =

(Asset impact) × (Number of those assets) × (Potential consequences)

This section outlines how this could be determined, with supporting details presented in Appendix D.

5.2 Direction

A requirement of this study is to establish, at a high level, a measure of the total potential impact of climate change on the deterioration of FCERM assets, and thus enable some ranking with identification of those assets that may require most attention going forward. The remit of the current phase is primarily to identify and develop an approach that can be subsequently applied, but it is also to provide initial indications based upon the information available at this stage.

To deliver on this objective requires some means to quantify impact, and there are three different forms this might take:

- Some measure of how much more deterioration takes place.
- Determining the extent of additional activity (work or cost) to deal with this.
- Measuring the consequences of not increasing maintenance/dealing with the issue (i.e. the resultant risk or damage to areas currently protected by the assets).

The level to which these can be delivered (e.g. generically or asset specific, number counts or investment requirements) depends upon the degree of quantification applied and the existence and resolution of the data to support this.

The first form of output is presently difficult to calculate, as outlined in Appendix C. This is in part because of a lack of a deterioration baseline against which to compare, and in part due to the variations that exist between individual assets and in different settings even for the same asset type. Furthermore, even if this is calculable, it is not obvious how to then use that information to inform the national picture.

There may be a series of analytical evaluations that can be conducted towards delivering the third output type, but essentially this requires a 'bottom-up' analysis with asset-specific assessment and understanding of how each of those assets contributes to the flood management system. Conclusions from the work to date indicate that without considerable additional data and knowledge it will be some time before it is possible to provide this. It is also complicated by a need to differentiate between the consequences being specifically deterioration related or performance related, which are not always clearly distinguishable.

The second output to quantify the level of additional activity (work or cost) required is, however, both deliverable and perhaps most relevant. This study is seeking to provide the knowledge and tools to help understand how climate change will affect deterioration for different asset types, and probably the most tangible impact is how this will alter the requirements to maintain those assets. This is consistent with the assessments that are presented in Appendices B and C, and is the recommended way forward to obtain an initial high level assessment of overall potential impacts.

5.3 Assessment

5.3.1 Requirements to support analysis

There are three primary requirements to support the analysis:

- asset impact
- number of assets
- potential consequences

These are scalable (i.e. each can be undertaken with relatively basic levels of information or refined as data and knowledge improves) and are further described below.

Asset impact

The means to determine which asset types are most vulnerable and establish the impact of climate change upon them is already well described in Appendices B and C, and is not repeated here.

With development, quantitative methods can be applied to establish the magnitude of impact upon those; that is, the amount of additional work required to address the change in vulnerability. In the meantime, to obtain an initial high level indication of overall impacts it is possible to use information from the qualitative assessments to:

- screen out those asset types that are least vulnerable and focus attention upon the remainder, primarily those that are categorised as ‘High’ and ‘Moderate’, and
- identify the nature of additional work that might be required so that an appropriate level of costs (i.e. consequence) might be attributed to that

Number of assets

National databases such as the AIMS (Asset Information Management System) database and the NCERM (National Coastal Erosion Risk Map) database contain information on asset numbers (e.g. the number of embankments or outfalls that exist). Although it is recognised that the quality of records in these are variable, the total asset count from them is reasonably reliable and allows some distinctions to be made between the main characteristics of these (e.g. percentage of each material type).

Ultimately it would be advantageous to further subdivide these asset types, for example so that the variations in structural form within each asset type, which might reflect variations in deterioration, were also identified and results can be refined accordingly. At the present time, however, the information available is sufficient to support a high level initial indication of overall potential impacts.

Potential consequences

The qualitative assessments (Appendix B) identified that the impacts of climate change on deterioration might require one of three response types:

1. More frequent maintenance/operation.
2. More regular/extensive repairs.
3. Substantial repairs/improvements.

Each one of these response types has a step increase in associated costs, and it would therefore be logical to establish for any climate change scenario whether the response, and cost, would fall into type ‘1’, ‘2’ or ‘3’.

Information on unit cost (e.g. per asset or per metre run, associated with each level of response; i.e. type ‘1’, ‘2’ or ‘3’), can be obtained or derived and applied accordingly. For example, for an embankment there is information from an Environment Agency cost capture exercise on the range of costs relating to response type 1, while published information exists on typical rates that might be applied to estimate costs for response types 2 and 3.

The extent and quality of data that presently exists on costs is discussed further in Appendix D. This comes from a variety of sources and with different assumptions, but sufficient information has been obtained to support application of the approach described here and provide the initial high level indication of overall potential impacts.

5.3.2 Present spend on asset maintenance

To provide a baseline against which to consider the cost of the impacts of climate change upon increased deterioration, it is important to understand how maintenance budgets are currently allocated.

The Environment Agency report *Technical and legal background to our asset maintenance*, published in February 2014, contains useful information on expenditure, presenting information from the previous 5 years. Over that period the average Flood Defence Grant-in-Aid (FDGiA) included:

- Capital allocation, of which on average approximately £250 million is spent on replacement (new schemes, major repairs and refurbishment).
- Revenue allocation, which includes on average approximately £160 million for a range of maintenance and operations related activities.

Of most relevance to this particular study is the proportion of revenue allocation which is direct costs on maintenance activities. Based upon information from recent years and discussion with the Environment Agency’s Allocation Team, a value for this of £84 million per year has been taken as a baseline for the assessments.

Maintenance activity has until recently also been further subcategorised as either:

- conveyance management

- MEICA
- operation of assets
- preventative maintenance on structures and defences

Across each of these there are then allocations made for 'frequent' and 'intermittent' activities, with an example definition under 'frequent maintenance' being:

- *Minor repairs (replace missing flap, joint repairs in flood wall, minor revetment repairs etc.) carried out during the course of frequent maintenance activities.*

And another example under 'intermittent maintenance' is:

- *Work involved repairing part of whole defence to reduce asset deterioration rate (more significant than those minor repairs covered by frequent maintenance).*

Based upon the definitions used for each of these and the apportionment of activities to each different category for various asset types, it is possible to conclude that the 'preventative maintenance' element of those costs is most directly relevant to addressing the potential deterioration aspects being considered by this study. Based upon information used to assess expenditure and develop budget allocations, the preventative maintenance has been calculated as likely to constitute approximately one-third of the total direct costs with a total 80:20 approximate split of that between frequent and intermittent expenditure.

The budget allocation of £84 million is roughly 20% lower than the amounts initially identified for maintenance each year, but that reduction results from the exclusion of uneconomic assets (i.e. where maintaining those would not return a benefit to cost ratio above unity). There is also an unbudgeted annual spend on reconditioning work to maintain current design life (REC). These are costs incurred over and above the regular budgets to carry out essential repairs. This varies year on year depending upon need, with expectations ranging from £2 to £10 million, although more recently the cost has been around £15 million per year.

In addition to the above are the costs that local authorities spend on maintaining and repairing coastal protection assets. Those costs are not centrally collated or distributed, so there is considerable variation from authority to authority, but information sought as part of this study indicates the total additional spend to be approximately £8 million per year.

5.3.3 Relating costs to asset-specific vulnerability

There are correlations that can be drawn between the categorisations of vulnerability level that have been derived through this study, the type of response required to address that, and the way in which budgets/actual expenditure is described and captured.

For example, as illustrated in Table 5.1, the type of response required to address some aspect of increased deterioration corresponds well with how maintenance budgets are defined.

Table 5.1 Relationship between type of response and budget allocation

Response required	Element of maintenance budget
More frequent maintenance/operation (type 1)	Frequent maintenance activities
More regular/extensive repairs (type 2)	Intermittent maintenance activities
Substantial repairs/improvements (type 3)	Refurbishment (capital works)

As listed in Section 5.3.1, there are different levels of unit costs that can be attributed to each response type for each asset type.

There are then different responses required depending upon the degree of vulnerability. The responses described also broadly correspond with the descriptions defined for qualitative assessments, as illustrated in Table 5.2.

Table 5.2 Relationship between vulnerability level and required response type

Vulnerability	Qualitative description	Response type
High	Change could result in a significant (large or rapid) increase in maintenance commitment and/or chance of failure due to deterioration	(3)+(2)+(1)
Moderate	Change likely to result in a notable increase in maintenance requirements or repair/replacement of elements due to deterioration but without significantly increasing failure probability	(2)+(1)
Low	Impacts may result in some small increases to the level of maintenance due to deterioration, e.g. the potential for some increase in the frequency of routine activities	(1)
Negligible	The impact of climate change factors on deterioration will result in little if any change to the maintenance of the asset	No change

Through these relationships it is possible to consider for any asset type with a certain level of vulnerability what the necessary type of response and corresponding level of costs might be to address that, and to also then establish which element of budget would be affected by that, and thus be able to compare with current levels of expenditure.

5.3.4 Application

To produce an initial high-level assessment of the total potential impact of climate change on the deterioration of assets, and to identify those assets that may require most attention going forward, an application of the approach has been conducted using currently available information. This is outlined in Appendix D, and summarised here.

As a first filter, only those asset types most likely to be affected by climate change were considered; that is, those where the vulnerability to deterioration is either ‘High’ or

‘Moderate’. The overall quantity of those was also obtained and, in doing so, a small number of asset types which had been categorised as having ‘Low’ vulnerability but of which there were considerable quantities (thousands) were also included. This combination of vulnerability to climate change and quantity for each asset type leads to an initial ranking of potential impact.

However, that gives no measure of consequence and the next step was to attribute unit cost rates for each response type and asset type to which increases to allow for the impacts of climate change might be applied and compared with current budgets to maintain, repair and refurbish FCERM assets.

The approach taken to calculate the impacts on annual maintenance and repairs has been to also consider other data pertaining to the reduction in return period for different events that may be encountered as a result of climate change. That can also be interpreted as the increase in frequency of exposure to those same events. Assuming deterioration rates are proportional to the level or frequency of exposure, if conditions that are currently experienced for example once every 2 years will in future be experienced annually, then it could be concluded that any deterioration resulting from those conditions may also occur twice as quickly. The extension of that is that the maintenance and repair activities necessary to address those conditions would also need to take place twice as often, in other words the present annualised costs for those would double.

Another finding of this study has been the future requirement to upgrade and improve certain assets to counter the potential for increased damage to structural elements and reduced structural integrity, as the asset will have been originally designed for lesser hydrodynamic loadings. That may take the form of increasing the size or nature of any protective cover layer or extending existing protection to prevent erosion of any presently unprotected surfaces for example. However, on the assumption that most assets are going to need major refurbishment or replacement anyway over the coming century, either due to long-term degradation in condition or raising to maintain performance standards, this study has estimated just the **additional** costs associated with any need to improve those assets over and above those existing requirements.

5.4 Results

5.4.1 Baseline

To put the results of the analysis into context, some benchmarking is useful:

- Present expenditure on the 11 assets with ‘High’ or ‘Moderate’ vulnerability is estimated to account for approximately two-thirds of the current frequent maintenance budget.
- Approximately 80% of current expenditure on intermittent maintenance is estimated to be spent on asset types categorised in this study as ‘High’ or ‘Moderate’ vulnerability.

It should be noted that the above are not figures provided or used by the Environment Agency or local authorities; they are the outcome of using the various data and interpreting them as described for the purposes of this study, and are applicable solely to the work presented here.

5.4.2 Maintenance and repair investment requirements

This analysis estimates the total increases in costs for maintenance and repairs due to the impacts of climate change to be between approximately £30 million and £75 million per year, as shown in Table 5.3.

In comparison to the current budget of approximately £92 million (£84 million Environment Agency plus £8 million local authorities), this represents an increase in required spending of between 32% and 82%.

The differences in increase between different environments are notable, with over 60% of the increase in maintenance costs and around 90% of the increase in repair costs being on coastal assets. This might be concluded to be simply attributable to the much higher uplift factors applied to coastal situations than in fluvial or estuarine settings, due to the use of a different dataset. But this outcome is not actually too surprising as there is an in-combination effect at the coast; the increase in sea levels (which is a constant and not solely event driven) also allows continual exposure to much larger waves which will be impacting upon those assets.

Table 5.3 Impacts of climate change on maintenance and repair costs

Increase in costs (£,000)		Total	Setting			
			Fluvial	Tidal River	Estuary	Coastal
MAINTENANCE	Min	**£6,900**	£1,700	£300	£400	£4,500
	Mean	**£19,700**	£4,500	£900	£1,300	£13,000
	Max	**£30,200**	£9,000	£1,800	£2,900	£16,500
REPAIR	Min	**£22,100**	£600	£100	£200	£21,200
	Mean	**£34,900**	£1,700	£300	£500	£32,400
	Max	**£45,000**	£3,800	£700	£1,200	£39,300
TOTAL	Min	**£29,000**	£2,300	£400	£600	£25,700
	Mean	**£54,600**	£6,200	£1,200	£1,800	£45,400
	Max	**£75,200**	£12,800	£2,500	£4,100	£55,800

In comparing the potential percentage increases in costs with existing budgets, REC has been deliberately excluded, but should not be ignored and can be assumed to be required in future in addition to these increases. Whether that might also need to be increased by a similar percentage to these budgets is not certain, but as this can already vary by a factor of 2 to 5, it may be assumed that the increase required in any particular year might also be within that range of present variability.

Table 5.4 shows the proportion of the estimated increase in maintenance and repair costs likely required for different asset types. This illustrates that just a few asset types are primary contributors to over 90% of the increases that have been determined.

Table 5.4 Ranking of impacts on maintenance and repair cost increases

Asset type	Setting	Proportion of additional cost
Embankments	Fluvial	26%
Coastal Embankments and Seawalls	Coastal	26%
Groynes	Coastal	20%
Embankments	Tidal River and Estuary	14%
River Walls and Bank Protection (High Ground)	Fluvial	8%
Outfalls	All	3%
Walls	Tidal River and Estuary	1%
All other asset types	All	2%

5.4.3 Refurbishment investment requirements

The magnitude of response type 3 activities (much more substantial repairs and refurbishment) make it meaningless to consider and compare these against maintenance budgets, so instead comparison is made with capital works expenditure.

This analysis estimates the total costs for such improvements is going to be in the range of £2.5 to £4.5 billion due to the impacts of climate change. To put that into context, based upon a present-day capital budget of £250 million per year for replacement of FCERM assets (new schemes, rebuilds etc.), this is the equivalent of 10 to 20 years of expenditure over and above 'business-as-usual'.

These would not be annual costs, but 'one-off' improvements to safeguard against the increased deterioration due to climate change, and assumed to be an extension of any works carried out at the same time as any requirement to rebuild or refurbish those assets due to them becoming life expired or needing improvement to maintain the required standard of protection.

Through this process it is clear that only a handful of the 80 asset type-setting combinations assessed are the major contributors to these increased costs, and it is those that warrant most attention going forward, whether that be in terms of additional and refined analysis or with respect to investment decisions.

Existing estimates of total rebuild costs for the three main asset types affected, Embankments, Walls and protected High Ground, indicate their replacement would be approximately £10 to £11 billion. Accommodating the improvements needed to address the impacts of climate change on the deterioration of those same assets, would therefore increase those costs by approximately 25% to 40%.

Table 5.5 shows the estimated increase in refurbishment costs likely to be required to make the improvements necessary for the most impacted assets to be able to counter the impacts of climate change upon deterioration.

Table 5.5 Asset types resulting in highest impacts on refurbishment costs

Asset type	Setting	Estimated cost (£ million)
Coastal Embankments and Seawalls	Coastal	£1,350–£1,625
River Bank Protection (High Ground)	Fluvial	£450–£1,025
Embankments	Fluvial	£375–£620
Embankments	Estuary	£190–£740
Walls	Estuary	£50–£210
Embankments	Tidal River	£100–£155
River Walls	Fluvial and Tidal River	£25–£50

6 Conclusions

6.1 Overview

With this research, we are increasing our understanding of how FCERM assets are vulnerable to various climate change factors. Forty-seven different asset types (both natural and man-made) and further subsets of those have been examined, across fluvial, estuary and coastal environments. The project has concentrated upon how certain changes in climate, such as increased sea levels or river flows, may affect the process of asset deterioration for each of those asset types, and which of those asset types will be most vulnerable to such changes.

The outcomes from the study include:

- Assessments, information and examples for flood and erosion risk management authorities to be able to better appreciate how the deterioration of different asset types could be affected by climate change.
- Providing those same flood and erosion risk management authorities with an understanding of the potential impact that various climate change factors could have upon asset maintenance and replacement activities.
- Identification of which asset types are likely to be most vulnerable to deterioration as a result of climate change, and appropriate tools to enable asset-specific assessments to be carried out.
- Approaches to identify where it may be necessary to target expenditure to address deterioration of those assets with greatest vulnerability to the effects of climate change.
- An initial high level estimate of the overall total impact of climate change upon FCERM asset deterioration, in terms of the possible level of additional investment required to address the issue.

6.2 Discussion on findings

6.2.1 Degradation

Material degradation will be a factor contributing to the deterioration of an asset. Although the mechanisms are well understood, rates of degradation are not well established; published information is wide-ranging at best and non-existent at worst. Most significantly, degradation rates are strongly influenced by factors such as quality of the material (e.g. concrete mix, timber type), location (e.g. steel buried, submerged, in splash zone) and exposure (e.g. to more dynamic conditions or abrasive agents). With huge uncertainty due to a lack of, or considerable variation in, published rates for present-day conditions, it therefore follows that predicting the effects of climate change upon material degradation rates is currently impossible.

This is therefore an area for improvement. One of the most significant causes of potential increased material degradation in FCERM assets appears to be abrasion, due to bed materials such as sands, silts and gravels mobilised more regularly and to a greater extent in more aggressive environments. This is perhaps an area where future research might be undertaken, to establish a more comprehensive baseline of material abrasion rates against which changes caused by climate might be predicted.

However, from the qualitative assessments made through this study, it can be concluded that the change in the rate of material degradation purely as a consequence of climate change is still likely to be of lesser significance on overall deterioration when compared to the effects of other environmental and physical factors. The more significant effect is the potential for deterioration of the asset as a whole (e.g. destabilising or damaging structural elements and reduction of structural integrity). These effects are also most likely to occur, and thus need to be addressed, over much shorter timescales compared to material degradation, which even with climate change will still be a slower and more gradual process.

6.2.2 Climate change factors

In considering how climate change may impact upon asset deterioration it is necessary to appreciate what form those changes will take. With respect to the four primary factors considered in this study, future sea level rise will have a constant (day-to-day) impact upon assets whereas changes to waves, surges and river flows, while becoming more frequent/regular, are generally going to be event driven. The impacts of each of these upon deterioration processes will therefore be different from each other. It is also important not to confuse natural variability in short-term weather events (e.g. over an hour, a day, or even interannually) with long-term trends (i.e. underlying changes which are taking place over several years and decades).

The four **primary** climate change factors selected for consideration in this study have been determined to be of most significance with regard to deterioration of assets; in considering the effects of four **additional** climate change factors, none of those increased the vulnerability of the assets over and above that concluded for the primary factors. In summary, the primary (hydrodynamic) climate change effects are likely to be the dominant cause of any change in deterioration for most assets where that change is sufficiently notable that the vulnerability is ‘Moderate’ or ‘High’.

6.2.3 Deterioration processes and vulnerability

The study has identified, for each generic asset type, the deterioration processes that are most likely to be affected by climate change. The assessments provided at this level are qualitative rather than quantitative. That is for a number of reasons, including in part the need to first filter out and prioritise where more intensive methods to analyse any impacts are warranted.

Based upon the qualitative assessments, the impacts of climate change upon deterioration of **fluvial** assets are assessed to be High or Moderate for approximately one-third of asset types. While this is not insignificant, another general conclusion drawn from those assessments is that the impacts of climate change upon capacity and performance are likely to require some upgrade to many assets before impacts from deterioration become the driver for major refurbishment.

Notwithstanding that, there will be a definite need to make improvements to address potential deterioration of those assets as well as dealing with performance-related issues. One example is higher river flows increasing the potential for erosion and displacement of the protective covering on embankments and river banks, while another is the erosion of the river bed (or bank) leading to displacement of other elements; neither of these problems would be addressed through simply defence raising to maintain performance (standard of protection) requirements.

The vulnerability of assets in a **coastal** environment are somewhat different from those in a fluvial setting. This results from the much more dynamic conditions that are experienced on the open coast by comparison, and the strong inter-relationships between the water levels, waves and local morphology that is regularly reshaped by those. Therefore, even modest changes in conditions as a result of climate change can have a significant impact.

In particular, almost all coastal asset types are vulnerable to instability created by beach lowering and greater direct wave forces upon the assets, increasing the potential for deterioration and destabilising of those assets. Beaches are noted as not simply being an asset in their own right, but having a significant bearing upon many other assets too. By contrast with the fluvial assets, the impacts of climate change upon deterioration have been qualitatively assessed to be High or Moderate for two-thirds of coastal asset types.

Within **estuaries**, climate change has been qualitatively assessed to have High or Moderate impact upon deterioration of approximately half of the asset types. A key determining factor in many cases will be where the asset is located; climate change factors and thus impacts in an open estuary and impacts in a tidal river can be quite different for the same asset type.

The categorisations developed and used by this study have enabled relationships to be developed between the level of vulnerability and the potential level of response required (e.g. increased maintenance and repair, or frequency of operation). In some cases, however, the change in deterioration may not require a corresponding incremental increase in activity but a need to change from one approach or system to another entirely (e.g. a protective cover layer of certain type needs to be replaced by a more robust form of protection, or the need to provide anti-erosion measures where there was no need before). This clearly has more significant implications in terms of cost.

It should also be noted that this study has looked generically across the whole asset base and there will be individual exceptions to the assumptions made. There are in fact several hundred 'major assets' maintained by the Environment Agency (such as the Thames Barrier, although the definition of major asset does not necessarily mean 'large'), which if significantly impacted by climate change might require a major investment in their own right. However, each would require specific examination which this current study has not attempted to analyse, but may warrant further consideration in the future.

6.2.4 Quantifying the effects of climate change on deterioration

The qualitative assessments now provide us with an excellent understanding of the ways in which climate change will affect the deterioration processes for each of the asset types, establishing those that are most important to understand.

To ascertain how much change in deterioration will take place, either in terms of extent or speed, some calculation is required. Methods to provide that have been appraised and examples provided, noting however that for several asset types or deterioration mechanisms there are no simple and easily applied methods to quantify change. Where such methods do exist they will in many instances require considerable (design-level) data to be applied.

Illustrative examples provide the practitioner with some useful insight into how to account for the effects of climate change in their future assessments. What those examples begin to demonstrate is the non-linear nature of the relationship between climate change and asset vulnerability; that is, there is no generic direct correlation between a percentage change in hydrodynamic condition and the change in damage/response required and it varies depending upon the deterioration mechanism that is most affected. It will also vary depending upon other factors such as the form of construction.

So, although broad-brush methods are required to be cost effective and practically applied with data that might be obtainable, the study identifies that approaches need to be able to take some account of the specific characteristics of the asset. However, there is considerable variation in the form of individual assets, including their geometry, material composition and design standards. Although the processes remain similar, each individual asset has the potential to be impacted to a different extent from others of that same generic asset type. The conclusion therefore drawn is that some level of asset-specific quantification using at the very least some basic parameters is necessary. This is achievable but the extent of data presently captured on these assets constrains our ability to do so at present, although this is clearly an area that could be improved upon.

6.2.5 Impact costs

An approach has been developed to calculate at a high level the overall impact that climate change may have upon asset deterioration by estimating the additional costs for maintenance and repair that may be required to address the issue. Despite some limitations of data, and with scope to improve upon those, this has been applied as part of this study to provide an initial high level indication of potential impact.

This analysis indicates that maintenance budgets may need to increase by between £30 and £75 million per year; an increase of 30% to 80% compared to that presently budgeted. To what extent this has a further knock-on effect upon additional indirect costs that also contribute to the £160 million per year annual budget has not been analysed, but it might be assumed that there will be some increase to those too, albeit probably to a lesser extent.

It should also be noted that the present-day budgets may themselves not be wholly reflective of actual requirements today; for example additional expenditure is already currently required and applied through REC. The full amounts required to keep pace with faster deterioration due to climate change may therefore require increasing to an even greater level than that estimated here.

While these increases in annual commitment are not insignificant, a more substantial investment requirement results from a need to upgrade and improve the robustness of the most vulnerable assets, to address the impacts of climate change upon their deterioration. Based upon this analysis that additional cost is estimated to be of the order of £2.5 to £4.5 billion. Based upon a present-day capital allocation of approximately £250 million for replacement (new schemes, major repairs and refurbishment), this could equate to 10 to 20 years of expenditure over and above 'business-as-usual' works for new schemes and asset replacements. The majority of these costs can be attributed to just a few asset types, with various forms of those categorised as 'Defences' featuring most heavily, notably embankments, walls and bank protection.

Here, it is worth stressing that the above investment requirements are all over and above the costs required to maintain and replace assets at present-day climate levels. They are also over and above the costs that will be necessary to address performance issues, that is raising defences or increasing capacity of assets to still provide the same standard of service delivered today, with climate change.

This therefore poses the question of whether the funding to keep pace with climate change will be available and, if not, what the alternatives are? Although these additional requirements will not be necessary for several years to come, it is necessary to begin to consider and plan for them now so that appropriate decisions are taken today.

An obvious option to help reduce both the annual maintenance increase and the need for major repairs is 'futureproofing' assets as and when they reach the end of their effective life and need to be replaced or subject to major reconstruction in the coming years. The methods presented in this study will help to identify what elements of defences need to be designed to withstand greater potential deterioration, and how to account for that in the design process.

This will spread some of the additional cost requirements over many more years, but it will also increase the costs of the works when carried out. In reality, what this tells us is that there would need to be a significant national flood and coastal defence improvement programme over the coming decades, commencing sooner rather than later, with the understanding provided by this study to be evolved and applied to inform any strategy for doing so.

Even if these costs are spread over several decades, this still requires considerable additional investment. If this is not possible, then the result will be that many more FCERM assets would not be maintained to the levels required, resulting in asset failures and flooding or erosion. This would be a risk however that would need to be managed proactively, and would require a change in management strategy; either withdrawing protection from some areas (and thus no longer managing those assets and adapting the land use), adopting lesser levels of protection for some areas (i.e. accepting increasing regularity of failures and more frequent flooding), or redefining the ways in which flood risks to certain areas are managed (i.e. changing the flood management system and asset types to more resilient forms).

The above approaches would all require considerable evaluation, taking account of a wide range of variables around costs and consequences to inform the correct decisions.

6.3 Recommendations

6.3.1 Use of methods for long-term scenario planning

This report presents the outcomes from the development phase of this project. It was originally planned to scope a subsequent application phase for calculating impacts, applying the methods provided. However, as it evolved it became clear that limitations on some of the data required would constrain that and, as deterioration cannot be considered in isolation, other initiatives such as the Environment Agency's LTIS (Long Term Investment Scenarios) programme might provide a more appropriate vehicle to apply some of these approaches at a national level in the future. The focus therefore changed to addressing some of the more specific questions arising, further developing the method to generate the initial high-level estimate of potential impacts (as described in Section 5 and discussed in Section 6.2.5). Notwithstanding that, an outline of how this might be taken forward by such other initiatives is given here.

This study only considered the deterioration of the asset as a consequence of defined climate change factors; it does not assess any change in standard of protection. However, in looking at deterioration of an asset we are taking account of a change in its ability to perform/function, and although an important distinction to be made, the inter-relationships are not always clearly distinguishable.

The study has also identified that there are analytical evaluations that can be conducted towards considering the impacts of increasing deterioration upon flood and erosion risk and damages. That would however require a 'bottom-up' spatial analysis which is beyond the requirements for this particular study but might be something for LTIS to consider further.

This might be incorporated through the NaFRA (National Flood Risk Assessment) which feeds modelled information into LTIS. The NaFRA project is currently looking at determining the future approach to national flood risk assessment, with a vision for a 'single, scalable assessment of flood risk' to be able to underpin long-term investment decisions. One element of that is to know how climate change will alter the current levels of risk, and including scenarios that also take account of deterioration would be a valuable addition to that.

The information from this study can help to inform this in two ways:

- The effects of climate change on asset deterioration, and thus potential requirements to alter maintenance and repair activities.
- The effects of climate change on asset performance, and thus potential requirements to improve/replace the assets.

What is apparent from the present work is that although these may be two different issues, some of the methods used to assess both are the same, as is much of the data that is needed to make that assessment. Examples of this include the overflow or overtopping of an embankment. A rise in water levels, having the potential for more water to discharge over the embankment, will increase both the risk and magnitude of flooding. But that higher flow can also result in more damage to the crest and rear surfaces and thus reduce the structural integrity, which increases the potential for breach or requires more maintenance/repair/improvement to prevent.

This study already provides some illustrations of how to quantify potential impacts of climate change on requirements for additional maintenance or repair activities. Not all processes are quantifiable, in part due to lack of existing knowledge on deterioration, and in part due to the lack of methods/techniques available to make that calculation. But some very straightforward equations and rules do exist for many of the different factors and the asset types that will be of most relevance in NaFRA (i.e. defences). The illustrations in Appendix C show how simple it can be to introduce these or similar equations into the NaFRA approach and to include an assessment of how maintenance or repair activities might alter with climate change, as well as more robust assessment of the effects of climate change on asset performance.

The inclusion of an assessment of potential increased maintenance commitment is achievable and will provide a more complete analysis of future investment requirements and thus an even more robust basis for deciding future strategy.

6.3.2 Data improvements

Maintaining a generic-level perspective for this particular analysis has its advantages. First, it has been possible to obtain outputs that will be broadly accurate across a set of assets, but without needing to analyse the nuances and peculiarities of each asset, which would require more precise data on each. Second, looking at the potential for impacts at a point in the future carries uncertainties in terms of the magnitude of any climate change and by when that will happen; changes in condition and indeed form of many assets that will inevitably occur by then. So, while asset-specific analysis is important for scenario planning, that detail is not required for calculating order of magnitude potential investment needs and general priorities for the future.

But the exploration of data and information for this study has also identified certain areas where improvements to data would be valuable for similar exercises in the future. Those include better definition of structural details in the national databases, to enable some of the critical geometric and other property details to be more identifiable so that engineering assessments such as this can make better use of those.

The second area is continuing to build better information on costs for various activities associated with the repair and refurbishment of assets. Although some additional useful information was obtained through the Environment Agency and engagement with a selection of local authorities, published information is very poor, so we continue to make some considerable assumptions with regard to the costs of doing work in the future.

6.3.3 Deterioration monitoring

Some of the questions arising while undertaking this study included:

- What is the baseline deterioration for each asset that climate change impacts can be compared against?
- How (and indeed can) a change in deterioration be quantified (what is the change or potential that is being measured)?
- How are the deterioration processes and impacts translated to timescales? Climate change is a continual but an accelerating change not a step change, and likewise some deterioration processes are not linear either.

To address the needs of this study, surrogates such as maintenance activities and costs, or methods to calculate different levels of damage, have been developed. These may indeed be most appropriate but still require some subjective interpretation as there is not currently any reliable information on deterioration rates for the various mechanisms that contribute to that deterioration (e.g. whether certain processes result in gradual or rapid change).

To rectify this, it would be useful to instigate a programme of deterioration monitoring, particularly if there are assets which are to be abandoned as the consequences of ‘no intervention’, so that actual rates can be ascertained and compared with similar maintained assets. Through this study we have identified several of the key processes that may affect deterioration for each asset type, and those process assessments can be used to define the monitoring required.

With the more significant changes in climate predicted to still be some years off, by commencing this now there is time to build a body of knowledge and a database that will be valuable to those having to manage this problem in 20 to 30 years’ time.

6.3.4 Dissemination and adoption of tools and techniques

The products from this project, in particular the deterioration process flow charts and assessments presented in Appendix B, and the quantification approaches presented in Appendix C, have been the subject of considerable interest from external bodies.

Some of this interest stems from presentations made to audiences from the Netherlands and the USA as part of the international Levee Partnership, which indicated that this is not something that currently exists elsewhere. In the UK, TEAM2100 have also expressed keen interest in utilising this information to help them develop their flood defence management programme for the Thames. Further dissemination activities are expected to generate further interest both nationally and internationally.

Emanating from this have been suggestions for additional products for practitioners based upon this research. Potentially the most valuable of those is the development of a ‘how to’ guide for engineers on using the information herein to make asset-specific assessments of deterioration and to apply this knowledge, for example to establish how to ‘futureproof’ designs or modify maintenance activities.

It is recommended that part of this would also include the expansion of the methods presented in Appendix C, to incorporate a wider range of deterioration mechanisms covering a greater variety of asset forms and characteristics, and taking account of differences in key relationships such as the environmental setting (e.g. exposure level, sediment type, beach volatility).

References

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