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Technical report – FCRM assets: deterioration modelling and WLC analysis

Report – SC060078

Flood and Coastal Erosion Risk Management Research and Development Programme

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Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

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Halcrow Group Limited

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Research Contractor:
Halcrow Group Limited, Burderop Park, Swindon, UK.

Environment Agency's Project Manager:
Stefan Laeger, Evidence Directorate

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Miranda Kavanagh

Director of Evidence

Executive summary

This technical report describes the technical methods, tools and data developed as part of the 'Assessment and Measurement of Asset Deterioration including Lifetime Costs' Phase 2 project being carried out by Halcrow Group Ltd for the Environment Agency.

A series of deterioration models and associated practical guidance (see separate SR1 report) have been developed to provide improved estimates of deterioration and residual life and to illustrate impacts of life-time costs.

The outputs support asset managers and operational staff within the Environment Agency in undertaking deterioration analysis, help to inform future management and maintenance and support planned work activities to optimise outcomes delivered through the maintenance programme.

A prototype Whole Life Costing Model has also been developed to illustrate how asset deterioration could be considered in WLC context as part of wider improvements to FCRM asset management systems.

The study covers a number of key asset classes, as listed in the following table:

Asset class	Material	AIMS asset classification (asset type, sub-type element)	Environment
Vertical walls (inc. with scour protection)	Concrete	Defence/wall	Fluvial
			Coastal/estuarine
	Brick and masonry		Fluvial
			Coastal/estuarine
	Timber		Fluvial
			Coastal/estuarine
	Gabion	Defence/wall/gabions	Fluvial
			Coastal/estuarine
Sheet piled structures	Anchored steel	Defence/wall/piling	Fluvial
			Coastal/estuarine
	Cantilever steel		Fluvial
			Coastal/estuarine
Demountable defences	Metal	Defence/demountable	Fluvial
	Wood		Fluvial
Earth dykes or embankments	Varying core material, e.g. clay, shale	Defence/embankment	Fluvial
			Coastal/estuarine
	With slope/toe protection or revetment		Fluvial
			Coastal/estuarine
Sloping walls with slope protection or revetment	Turf	Defence/embankment	Fluvial
			Coastal/estuarine
	Permeable revetments		Fluvial
			Coastal/estuarine
	Impermeable revetments		Fluvial
			Coastal/estuarine
Culverts – pipe, box, arch	Concrete/masonry/brick	Channel/simple OR complex culvert	Fluvial
	Steel		Fluvial
	Plastic		Fluvial
	Clay		Fluvial
Beaches with and without beach control structures (rock/timber groynes), offshore breakwaters (rock), breastwork (timber)	Shingle/sand	Defence/beach	Coastal/estuarine

Asset class	Material	AIMS asset classification (asset type, sub-type element)	Environment
and crib walls (timber)			
Control structures	Rock groynes	Beach structure/groyne	Coastal
	Timber groynes		Coastal
	Offshore breakwaters (rock)	Beach structure/breakwaters	Coastal
	Crib walls and breastwork		Coastal
Dunes with or without holding structures		Defence/dunes	Coastal
Saltmarshes, saltings and warths with or without holding structures		Land/saltmarsh	Coastal/estuarine
Maintained channel	Earth (e.g. regraded channel) Concrete	Channel/open channel	Fluvial
Weirs		Structure/weir	Fluvial
Outfalls		Structure/outfall	Fluvial
			Coastal
Flap valves, penstocks and sluice gates (manually and electrically operated moveable gates)		Structure/control gate	Coastal/fluvial
Debris screens		Structure/screen	Fluvial
Flood gates and barriers	Metal	Structure/control gate	Coastal/fluvial
	Wood		Coastal/fluvial

The prototype tool illustrates how asset condition profiles and whole life cost profiles can be displayed for a selected asset type under various scenarios representing various combinations of:

- location (either fluvial or coastal/estuarine);
- planned maintenance regime: (1) basic, (2) medium or (3) high levels of maintenance activity based on defined Environment Agency standards;
- likely deterioration rate (as influenced by environment (sheltered to exposed) and quality of materials/construction (poor to good)).

The prototype tool shows how whole life costs are estimated for current Environment Agency maintenance practice (which for a number of assets is typically basic level activity) and the impact of alternatives of increased maintenance activity to be assessed.

The deterioration model and prototype WLC tool have been developed with the objective of delivering robust (i.e. operationally implementable) methods and models for assessing the deterioration and whole life cost profiles of important Flood and Coastal Risk Management (FCRM) assets under different maintenance regimes in order to provide improved estimates of deterioration, residual life and lifetime costs. The prototype tool is adaptable to further development outside the scope of this project including incorporation of benefit analysis and optimisation components as part of a wider approach to managing FCRM assets and data systems.

Acknowledgements

The authors would like to thank the Environment Agency staff who have contributed to the development of the methods and tools described in this report. In particular, the efforts of Lindsay Hensman, Project Executive, and Stefan Laeger, Client Project Manager, are recognised. We would also like to thank our colleagues in Halcrow for their comments and suggestions.

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1 Introduction

1.1 Rationale for this work

Flood and Coastal Risk Management (FCRM) assets within England and Wales are worth approximately £35 billion (replacement value). To continue to provide protection to people from flooding and erosion, these assets require appropriate levels of maintenance and repair that are consistent with the rate of deterioration caused by numerous material, physical and environmental factors. Reliable and comprehensive information on asset deterioration and the effect on this of various maintenance options is not readily available. However, such information is essential for the effective management of FCRM assets.

R&D project SC060078 on 'Assessment and Measurement of Asset Deterioration including Lifetime Costs' aims to fill this gap by increasing our understanding of how FCRM assets deteriorate. This study focuses on sustainable asset management to enable a better understanding of deterioration processes. The study objective is to provide predictive models to generate asset condition and performance profiles for future timeframes. The study is funded as part of the Joint Environment Agency/Defra Flood and Coastal Erosion Risk Management (FCERM) R&D Programme.

An aim of this project is to examine how deterioration influences asset condition and performance under different maintenance regimes. This is of particular importance, since an understanding of deterioration is vital for planning maintenance programmes, and renewal intervention activities, to control asset condition and performance to acceptable levels.

A prototype whole-life-cost analysis model illustrates the benefits of considering asset deterioration in a whole-life-cost context For a given maintenance regime the deterioration model determines how the asset condition grade changes over time in relation to maintenance of varying activity type and frequency, while the whole life costing (WLC) model determines how the costs develop. These models can then be used to determine the preferred maintenance regime, taking account of criteria such as condition targets, available budget and benefit/cost ratio.

Phase 1 of the project collected available knowledge from both literature and Environment Agency and maritime local authority asset managers. This provided a basis for assessing deterioration at the individual asset level and developing deterioration curves for a number of key FCRM assets. Each deterioration curve sets out the time spent at a condition grade over the lifetime of an asset in relation to the level of maintenance and estimated rate of deterioration. The work from Phase 1 is summarised in Appendix 2 of the report *Guidance on Determining Asset Deterioration and the Use of Condition Grade Deterioration Curves*, Environment Agency R&D Project SC060078.

This commission is the second phase of this research project. The methodologies in this phase of the project are designed to complement and build upon the work from Phase 1 of the project.

1.2 Aims and objectives

The aims of the project are to design and implement a targeted data collection and monitoring programme to support the gathering of records on asset deterioration and the cost-effectiveness of different maintenance strategies. Asset management models and prototype tools are to be developed and tested for predicting asset deterioration and for undertaking whole life cost/benefit analysis.

The specific objectives of the Phase 2 study are:

Objective 1: To develop and conduct a targeted data collection monitoring programme for key FCRM assets to improve our understanding of how key FCRM assets deteriorate.

Objective 2: To investigate the processes of deterioration and to develop and test practical methods and models for assessing the deterioration of important FCRM assets in order to provide improved estimates of deterioration and residual life.

Objective 3: To develop and test methods and models for assessing whole life costs under different maintenance regimes for selected asset types which are robust enough to be considered for use by operational staff.

Objective 4: To develop improved practical guidance on determining asset deterioration and assessing the effects of different maintenance regimes.

Figure 1.1 illustrates the various stages of the project and associated activities.

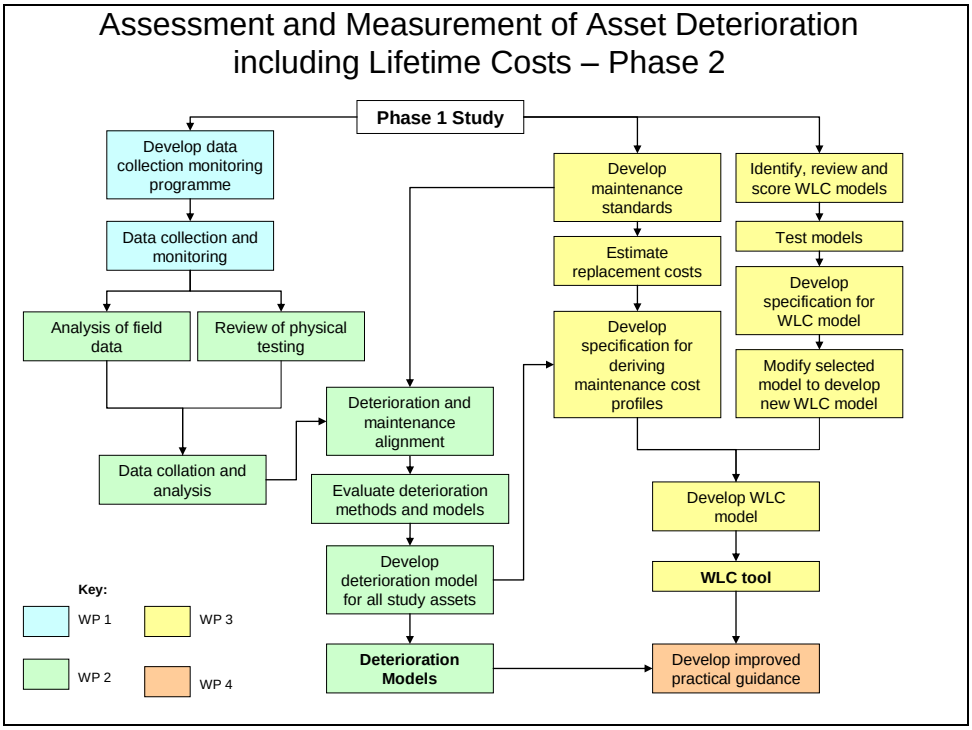

Figure 1.1 Summary of Work Packages (WP) 2 and 3

1.3 This report

This technical report describes the technical methods, tools and data developed during work undertaken to fulfil objectives 2 and 3 above, specifically:

- Developing and testing robust methods and models for assessing asset deterioration (Work Package 2).
- Developing and testing methods and models for assessing whole life costs under different maintenance regimes for selected asset types (Work Package 3).

The full range of asset types covered by the project is listed in Section 2. Details of the work undertaken and outcomes for the deterioration model development and the prototype whole life cost analysis tool development are in Sections 3 and 4 respectively.

Section 5 presents conclusions and recommendations.

Additional material is presented in the appendices:

- Appendix A: Deterioration models – asset by asset (issued separately).
- Appendix B: Maintenance standards developed during the project (issued separately).
- Appendix C: Asset replacement costs.

2 Project scope: FCRM assets

At the start of the project (August 2009), FCRM assets included in the project scope were identified. Table 2.1 lists these asset types and their environment.

Table 2.1 List of assets covered by project Phase 2

Asset class	Material	AIMS asset classification (asset type, sub-type element)	Environment
Vertical walls (inc. with scour protection)	Concrete	Defence/wall	Fluvial
			Coastal/estuarine
	Brick and masonry		Fluvial
			Coastal/estuarine
	Timber		Fluvial
			Coastal/estuarine
	Gabion	Defence/wall/gabions	Fluvial
			Coastal/estuarine
Sheet piled structures	Anchored steel	Defence/wall/piling	Fluvial
			Coastal/estuarine
	Cantilever steel		Fluvial
			Coastal/estuarine
Demountable defences	Metal	Defence/demountable	Fluvial
	Wood		Fluvial
Earth dykes or embankments	Varying core material, e.g. clay, shale	Defence/embankment	Fluvial
			Coastal/estuarine
	With slope/toe protection or revetment		Fluvial
			Coastal/estuarine
Sloping walls with slope protection or revetment	Turf	Defence/embankment	Fluvial
			Coastal/estuarine
	Permeable revetments[1]		Fluvial
			Coastal/estuarine
	Impermeable revetments[2]		Fluvial
			Coastal/estuarine
Culverts – pipe, box, arch	Concrete/masonry/brick	Channel/simple OR complex culvert	Fluvial
	Steel		Fluvial
	Plastic		Fluvial
	Clay		Fluvial
Beaches with and without beach control structures (rock/timber groynes), offshore breakwaters (rock), breastwork (timber) and crib walls (timber)	Shingle/sand	Defence/beach	Coastal/estuarine

[1] Permeable revetments: These are flexible revetments including rip-rap, turf, natural stone and concrete blocks.
[2] Impermeable revetments: These are continuous sloping structures of concrete or stone blockwork, asphalt or mass concrete. They tend to be grouted in bitumen or concrete, making them inflexible.

Asset class	Material	AIMS asset classification (asset type, sub-type element)	Environment
Control structures	Rock groynes	Beach structure/groyne	Coastal
	Timber groynes		Coastal
	Offshore breakwaters (rock)	Beach structure/breakwaters	Coastal
	Crib walls and breastwork		Coastal
Dunes with or without holding structures		Defence/dunes	Coastal
Saltmarshes, saltings and warths with or without holding structures		Land/saltmarsh	Coastal/estuarine
Maintained channel	Earth (e.g. regraded channel) Concrete	Channel/open channel	Fluvial
Weirs		Structure/weir	Fluvial
Outfalls		Structure/outfall	Fluvial
			Coastal
Flap valves, penstocks and sluice gates (manually and electrically operated moveable gates)		Structure/control gate	Coastal/fluvial
Debris screens		Structure/screen	Fluvial
Flood gates and barriers	Metal	Structure/control gate	Coastal/fluvial
	Wood		Coastal/fluvial

3 Deterioration modelling

3.1 Introduction

The deterioration model construction process involved the following series of steps:

- Review of deterioration data relating to FCRM assets (Section 3.2).
- Review and appraisal of deterioration modelling approaches (Section 3.3).
- Development of generic deterioration modelling approach (Section 3.4).
- Development of individual deterioration models (application to asset types) (Section 3.5).

3.2 Review of deterioration data

To support the understanding of deterioration and the development of new models based on real data, various data and information relating to deterioration processes of FCRM assets have been examined and reviewed.

A variety of data sources was used. These comprised:

- Phase 1 report for the project SC060078 'Assessment and Measurement of Asset Deterioration including Lifetime Costs'.
- Field data from Work Package 1 (of this study) covering 76 sites.
- Historical information relating to 40 of the 76 field trial sites (available from the Environment Agency's National Flood and Coastal Defence Database (NFCDD) (the other 36 sites had no associated data).
- Wider asset data from the Environment Agency database NFCDD (records for 3917 assets were suitable for inclusion in model construction).
- Literature within the public domain.

The data review is fully documented in the project yearly summary report (Year 2, November 2011). The application of these data sources to individual asset types is shown in Section 3.5 (see Section 3.5.2 and Table 3.9 for details) and in Appendix A for individual models.

It is of note that the monitoring programme (Work Package 1) was set up to record condition data on specific types of assets that were considered not to be otherwise well represented in terms of deterioration data. These included:

- Vertical walls – brick and masonry
- Earth dykes/embankments
- Sloping walls with slope protection or revetments
- Control structures – timber groynes

This monitoring has included visual-inspection surveys and physical/intrusive surveys and was undertaken during Year 1 of the study (2010) and as a repeat exercise for Year 3 (during the first part of 2012). These surveys have provided information on the current condition grade of the assets, deterioration processes and likely failure modes if deterioration is allowed to continue.

It is recognised that the 3-year duration of the project may not provide sufficient time for deterioration processes to have a marked or even noticeable progressive effect on the condition of the study assets. The principal value of the monitoring data is therefore as validation data for the deterioration curves. Through alignment of the individual asset's condition grade and age (as recorded in the Environment Agency database), it is possible to assess whether the deterioration model predictions are consistent with the assets inspected.

Recognising the slow pace of change, continued targeted monitoring beyond the 3 years of the project would be useful to improve estimates of asset deterioration in future.

A conclusion of the data review is that the various data and information collected (historical and new) are suitable, in combination, to inform the construction, validation and calibration of the deterioration curves.

3.3 Review and appraisal of deterioration modelling approaches

3.3.1 Introduction

In order to assess the methods and models for the development of robust predictive deterioration models, it was necessary to examine several issues. These were:

1. Key deterioration mechanisms and failure modes of the assets (Section 3.3.2).
2. The impact of maintenance (Section 3.3.3), addressing the following:
    - What maintenance/refurbishment options are available for the different deterioration mechanisms?
    - What maintenance practices can realistically achieve and how the degree of maintenance will affect overall life?
    - Mapping of asset deterioration processes with maintenance activities.
3. Suitable existing deterioration models (Section 3.3.4).

Through consideration of the above, a methodology was developed which complements and builds upon the technical developments and outputs from Phase 1 of the project (Section 3.4).

3.3.2 Understanding key deterioration mechanisms and failure modes

Deterioration processes for key FCRM assets are shown in Table 3.1, which lists all asset types for which deterioration curves have been developed.

The table also gives an estimate of design life (currently used for establishing whole life costs and estimates of replacement) and of actual life (well maintained and under a 'do nothing' option). Estimates of actual life have been made based on engineering experience of the ages of existing functioning assets in the UK today.

The failure modes have been adopted from the Performance-based Asset-Management Systems (PAMS) study (Defra/Environment Agency 2004, Environment Agency 2009b). Dominant failure modes are those where the related performance features (where a performance feature is a feature of a defence asset which is related, directly or indirectly, to the performance of that defence asset) are given the greatest weighting in the Condition Index Methodology tables for each asset in the PAMS condition inspection method (Environment Agency 2009a, Section 3.6). These failure modes have been shown to be the most likely to occur, based on engineering experience and judgement. The table also lists all the indicators of deterioration (i.e. reduction in performance). Dominant deterioration processes have also been identified as those most likely to influence the rate of deterioration for each asset type.

Table 3.1 Deterioration processes

Asset class	Material	Environmental factors	Asset type (NFCDD database)	Typical design life	Potential max. asset life (assuming maintenance)	Estimated asset life for 'do nothing' option	Failure modes	Dominant failure modes	Indications of poor performance/deterioration	Dominant deterioration processes
Vertical walls (inc. with scour protection)	Concrete	Fluvial	Raised defence (man-made)	50	200	100	Horizontal sliding Rotational slip Overturning Piping Backfill washout Bearing capacity failure Structural failure Overtopping leading to breach	Scour leading to undermining Rotational slip	Movement in or loss of surrounding supporting strata Settlement Undermining Exposure/corrosion of reinforcement Honeycombing, flaking or spalling of concrete Abrasion damage Corrosion of concrete units Sealant or joint fill material loss Washout of fill Cracks or fissuring Evidence of leakage through or beneath the wall Vandalism Failure or damage to scour protection Chemical damage to timber components Insect damage, rot or decay of timber components Deformation of gabions Corrosion and breakage of wires in gabions Missing bricks/blocks or loss of fill material in gabions	Toe scour Damage to scour protection Movement of structure
		Coastal/estuarine	Raised defence (man-made)	50	200	60				
	Brick and masonry	Fluvial	Raised defence (man-made)	50	200	100		Scour leading to undermining Rotational slip Disintegration of elements leading to structural failure Washout of fill leading to settlement		Toe scour Damage to scour protection Washout of fill Damage to joints Disintegration of components Movement of structure
		Coastal/estuarine	Raised defence (man-made)	50	200	60				
	Timber	Fluvial	Raised defence (man-made)	25–40	100			Scour leading to undermining Disintegration of elements leading to structural failure Washout of fill leading to settlement		Toe scour Disintegration of components Washout of fill Movement of structure
		Coastal/estuarine	Raised defence (man-made)	25–40	100					
	Gabion	Fluvial	Raised defence (man-made)	50	60	10		Scour leading to undermining Disintegration of elements leading to structural failure Washout of fill leading to settlement		Toe scour Disintegration of basket/rock packing Washout of fill Movement of structure
		Coastal/estuarine	Raised defence (man-made)	50	60	10				
Sheet piled structures	Anchored steel	Fluvial	Maintained channel	50	150	100	Rotational slip Rotation Anchor failure Piping Backfill washout Structural failure Overtopping leading to breach	Scour leading to rotation Disintegration of elements leading to fill washout and structural failure	Movement in or loss of surrounding supporting strata Settlement Undermining Corrosion of sheet piles or reinforcement including ALWC (Accelerated Low Water Corrosion) Fatigue of steel Chemical damage to timber piles Insect damage, rot or decay of timber piles Damage to structural components (e.g. tie-rod or anchorage system) Abrasion damage Evidence of leakage through or beneath the wall Vandalism	Toe scour Disintegration of components Washout of fill Movement of structure
		Coastal/estuarine	Raised coastal defence (man-made)	50	150	60				
	Cantilever steel	Fluvial	Maintained channel	50	150	100		Scour leading to rotational slip Disintegration of elements leading to fill washout and structural failure		Toe scour Disintegration of components Washout of fill Movement of structure
		Coastal/estuarine	Raised coastal defence (man-made)	50	150	60				
Demountable defences	Metal	Fluvial	Raised defence (man-made)	50	80		Structural failure Operation error Third party interference/ obstruction	Disintegration of elements leading to structural failure Operation error Third party interference/ obstruction	Support walls damaged or collapsed Obstruction preventing deployment/erection Anchorage points damaged or missing Gaps present between elements Corrosion/decay of elements Seals missing or perished Handling points damaged/missing	Disintegration of components Third party interference/ obstructions
	Wood	Fluvial	Raised defence (man-made)	25–40	80					
Earth dykes or embankments	Varying core material, e.g. clay, shale	Fluvial	Raised defence (man-made)	50–100	500	100	Slope instability Revetment failure Piping Backfill washout Overtopping leading to breach	Backfill washout Piping Overtopping leading to breach	Movement in or loss of surrounding supporting strata Settlement Undermining Lateral movement or sliding	Backfill washout Animal burrows Structural damage to slopes/crest Movement of structure

Asset class	Material	Environmental factors	Asset type (NFCDD database)	Typical design life	Potential max. asset life (assuming maintenance)	Estimated asset life for 'do nothing' option	Failure modes	Dominant failure modes	Indications of poor performance/deterioration	Dominant deterioration processes
		Coastal/estuarine	Raised coastal defence (man-made)	50–100	500	100			Loss of fines due to seepage/infiltration Cracking or fissuring Shallow failures within slope Crest or slope damage from animals, vehicles or people Vegetation damage or loss Erosion/scour of embankment Evidence of seepage through or beneath the embankment Vandalism Damage to revetment/scour protection	
	With slope/toe protection or revetment	Fluvial	Raised defence (man-made)	50–100	500	100		Revetment failure Backfill washout Piping Overtopping leading to breach		Damage to slope protection/ revetment Backfill washout Animal burrows Structural damage to slopes/ crest Movement of structure
		Coastal/estuarine	Raised coastal defence (man-made)	50–100	500	100				
Sloping walls with slope protection or revetment	Turf	Fluvial	Maintained channel	50	500		Slope instability Revetment failure Piping Fill washout Overtopping leading to breach	Revetment failure Washout of fill Piping	Movement in or loss of surrounding supporting strata Settlement Undermining Lateral movement or sliding Loss of fines due to seepage/infiltration Cracking or fissuring Shallow failures within slope Crest or slope damage from animals, vehicles or people Vegetation damage or loss Erosion/scour of embankment Evidence of seepage beneath the embankment Vandalism Damage to revetment/scour protection	Damage to slope protection/ revetment Toe scour Washout of fill Structural damage to slope Movement of structure
		Coastal/estuarine	Raised coastal defence (man-made)	50	500					
	Permeable revetments	Fluvial	Maintained channel	50	200	100				
		Coastal/estuarine	Raised coastal defence (man-made)	50	200	60				
	Impermeable revetments	Fluvial	Maintained channel	50	200	100				
		Coastal/estuarine	Raised coastal defence (man-made)	50	200	40				
Culverts – pipe, box, arch	Concrete/ masonry/brick	Fluvial	Culverts Brick/concrete/stone/plastic/ ferrous/clay	50	200	100	Settlement Blockage Structural failure	Blockage Structural failure	Deformation to culvert Settlement to invert or soffit Cracking, fissuring, or spalling of concrete or other components Corrosion to elements Missing bricks/blocks Sealant or joint fill material loss Vegetation growth inside culvert/root penetration	Disintegration of components Leakage/interruption to drainage Movement of structure
	Steel	Fluvial	Culverts Brick/concrete/stone/plastic/ ferrous/clay	50	150					
	Plastic	Fluvial	Culverts Brick/concrete/stone/plastic/ ferrous/clay	50	150					
	Clay	Fluvial	Culverts Brick/concrete/stone/plastic/ ferrous/clay	50	200					
Beaches with and without beach control structures (rock/timber groynes), offshore breakwaters (rock), breastwork (timber) and crib walls (timber)	Shingle/sand	Coastal/estuarine		-	-		Insufficient cross-sectional area Gulleying Overtopping leading to breach	Insufficient cross-sectional area	Continuous reduction in cross-sectional area or extent over long term Extensive reduction in cross-sectional area or extent due to extreme event Damage to control structures Vegetation damage or loss on saltmarshes and dunes Gulleying Percolation through the beach Third party damage, e.g. boat damage Wind erosion	Slope condition

Asset class	Material	Environmental factors	Asset type (NFCDD database)	Typical design life	Potential max. asset life (assuming maintenance)	Estimated asset life for 'do nothing' option	Failure modes	Dominant failure modes	Indications of poor performance/deterioration	Dominant deterioration processes
Control structures	Rock groynes	Coastal	Coastal erosion protection assets	50	200		Undermining Settlement Structural failure	Structural failure	Voids in rock packing Extents of loosely packed rock Settlement of rock Exposure of rock toe Damage to exposed geotextile layer Loss of rock armour or infill	Disintegration of rock packing Movement of structure Exposure of rock core/geotextile
	Timber groynes Timber crib walls and breastwork	Coastal	Coastal erosion protection assets	25–40	100	10 to 25	Loss of elements Structural failure	Loss of planks Structural failure	Missing or damaged planks Missing or damaged ties, walings and fixings Groyne no longer able to arrest drift of beach material Movement, rotation, bulging or undermining	Disintegrated or missing components Movement of structure
	Offshore Breakwaters (rock)	Coastal	Coastal erosion protection assets	50	150		Settlement Structural failure	Structural failure	Voids in rock packing Extents of loosely packed rock Settlement of rock Exposure of rock toe Damage to exposed geotextile layer Loss of rock armour or infill	Disintegration of rock packing Movement of structure Exposure of rock core/geotextile
Dunes with or without holding structures		Coastal	Raised coastal defence (natural)	-	-		Insufficient cross-sectional area Gulleying Overtopping leading to breach	Insufficient cross-sectional area	Narrow or flat dune system Damage or loss of vegetation Low beach fronting dunes Erosion or collapse of seaward dune slope Evidence of overtopping, i.e. runnels Damage to control structures Third party damage, e.g. boat damage Presence of foreign objects	Slope condition Vegetation condition
Saltmarshes, saltings and warths with or without holding structures		Coastal/estuarine		-	-		Insufficient cross-sectional area Gulleying Overtopping leading to breach	Insufficient cross-sectional area	Steep and narrow slope Erosion of marsh toe Widening and lengthening of creek system Vegetation loss or damage Third party damage, e.g. grazing Exposed underlying mud flat Presence of foreign objects	Slope condition Vegetation condition
Maintained channel	Earth (e.g. regraded channel) Concrete	Fluvial	Maintained channel	50–100	200	100	Blockage Structural failure of banks	Blockage Structural failure of banks	Overgrown vegetation Signs of sediment deposits Trash deposits Foreign objects present	Leakage/interruption to flow Movement of banks
Weirs		Fluvial	Flood defence structures	50	200	100	Structural failure Siltation Blockage Undermining Settlement	Structural failure Siltation Blockage Undermining Settlement	Cracks, erosion or damage to crest, apron or wing walls Uneven flow over crest Sediment deposits on upstream face Signs of erosion at structure sides/undermining Loss of revetment at structure sides Movement of abutments or wing walls Vegetation encroachment Evidence of leaching or water bypassing Settlement Blockwork or mortar missing	Disintegration of elements Foreign materials/blockage Movement of structure

Asset class	Material	Environmental factors	Asset type (NFCDD database)	Typical design life	Potential max. asset life (assuming maintenance)	Estimated asset life for 'do nothing' option	Failure modes	Dominant failure modes	Indications of poor performance/deterioration	Dominant deterioration processes
Outfalls		Fluvial		50	200	100	Settlement Undermining Blockage Structural failure	Blockage Structural failure	Pipe broken or blocked Discharge outlet buried or blocked Movement or settlement Scour or undermining Cracks in main structural elements Broken timbers Leaking pipe Loss of thickness of piles due to corrosion, abrasion, etc Fixings failing or missing	Disintegration of elements Leakage/interruption of flow Movement of structure
		Coastal	Flood defence structures	50	200	60				
Flap valves, penstocks and sluice gates (manually and electrically operated moveable gates)		Coastal/fluvial	Flood defence structures	25–50	80		Mechanical failure Siltation Blockage Structural failure	Mechanical failure Blockage Structural failure	Mechanism seized, operation compromised Gate timbers rotten or missing Flap has lost support, been damaged, has moved, is missing or is unable to operate Corrosion, leakage, siltation or blockage Damaged or missing mountings or fixings Hinge bolts worn, corroded or missing Siltation preventing operation Deterioration of headwall	Disintegration of elements Obstructions
Debris screens		Fluvial	Flood defence structures	50	80		Blockage Structural failure	Blockage Structural failure	Corrosion of bars and fixing elements Defects to bars, fixing or headwalls Bar spacing distorted Screen missing or not fixed correctly Headwall missing Mortar loss or surface spalling of headwall	Leakage/interruption to flow Obstructions Disintegration of elements
Flood gates and barriers	Metal	Coastal/fluvial	Flood defence structures	50	80		Structural failure Third party interference/ obstruction Operation error	Structural failure Third party interference/ obstruction Operation error	Damage to or gaps in gate or barrier Gate seals damaged, failed or missing Locking mechanism damaged, seized or missing Hinges difficult to operate Distortion of gate or frame Gate missing or obstructed Cracking of concrete/brickwork	Disintegration of elements Third party interference/ obstructions Operation error
	Wood	Coastal/fluvial	Flood defence structures	50	80					

3.3.3 Understanding impact of maintenance and refurbishment

The Environment Agency has defined maintenance standards for routine maintenance activities on FCRM assets. An Environment Agency manual[3] introduces these standards along with detailed descriptions of activity levels and unit costs for a number of the study assets. The manual sets out maintenance activities and costs for a range of asset types for specific target condition grades.

These maintenance standards are aligned with target condition grades (CG) and identify a range of maintenance activities at various frequencies to maintain assets at one of three options: CG 2, 3 and 4, denoted high, medium and basic respectively (Table 3.2).

Table 3.2 Maintenance standards and alignment with condition grades

Maintenance standard	Target condition grade	Description
High	2 – Good	Only allow minor defects that will not reduce performance of the asset
Medium	3 – Fair	Allow some defects that could reduce performance of the asset
Basic	4 – Poor	Allow defects that significantly reduce the performance of the asset

Practical application of these maintenance standards is influenced by ongoing deterioration. It cannot be assumed that an asset can be kept at a specific condition grade indefinitely (i.e. over the whole life cost period). Despite maintenance there will be some deterioration and change to condition grade. It is often necessary to refurbish during the life of the asset to ensure continued serviceability and adequate performance.

In order to develop deterioration curves linked to maintenance practices it is necessary to consider the following questions:

- What maintenance and refurbishment options are available and how effective are they for controlling asset deterioration?
- Which deterioration mechanisms can be controlled through maintenance and which ones cannot?
- How does the degree of maintenance affect overall asset life?
- To what extent can operational maintenance prevent asset deterioration?
- What constitutes asset refurbishment in contrast to the Environment Agency standard maintenance practices and when is it likely to become a necessity?

To improve understanding a mapping exercise comparing asset deterioration processes with maintenance activities was undertaken. Table 3.3 presents the results.

[3] Environment Agency, 2010 (March). *Delivering Consistent Standards for Sustainable Asset Management, FCRM Asset Management Maintenance Standards, Version 2*.

Table 3.3 Mapping of deterioration processes and maintenance activities

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Vertical walls (inc. with scour protection)	Concrete	Fluvial Coastal/ estuarine	1. Movement in or loss of surrounding supporting strata 2. Settlement 3. Undermining 4. Exposure/corrosion of reinforcement 5. Honeycombing, flaking or spalling of concrete 6. Abrasion damage 7. Corrosion of concrete units 8. Sealant or joint fill material loss 9. Washout of fill 10. Cracks or fissuring 11. Evidence of leakage through or beneath the wall 12. Vandalism 13. Failure or damage to scour protection	1. Partially by scour protection and backfill replacement 2. No 3. Partially by scour protection 4. Partially by repair of concrete before reinforcement exposed 5. Partially by repair of concrete 6. Partially by repair of concrete and sealant replacement/repair 7. No 8. Yes by joint repair 9. Partially by backfill replacement 10. Partially by repair of concrete 11. Possibly by minor repair works 12. Dependent on form of vandalism 13. Yes by scour protection

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Vertical walls (inc. with scour protection)	Brick and masonry	Fluvial Coastal/ estuarine	1. Movement in or loss of surrounding supporting strata 2. Settlement 3. Undermining 4. Abrasion damage 5. Damage to brickwork 6. Sealant or joint fill material loss 7. Washout of fill 8. Cracks or fissuring 9. Evidence of leakage through or beneath the wall 10. Vandalism 11. Failure or damage to scour protection	1. Partially by scour protection and backfill replacement 2. No 3. Partially by scour protection 4. Partially by replacement of damaged bricks and joint repair 5. Partially by replacement of damaged bricks 6. Yes by joint repair 7. Partially by backfill replacement 8. Partially by minor repair works and replacement of damaged bricks 9. Possibly by minor repair works 10. Dependent on form of vandalism 11. Yes by scour protection
Vertical walls (inc. with scour protection)	Timber	Fluvial Coastal/ estuarine	1. Movement in or loss of surrounding supporting strata 2. Settlement 3. Undermining 4. Abrasion damage 5. Washout of fill 6. Vandalism 7. Failure or damage to scour protection 8. Chemical damage to timber components 9. Insect damage, rot or decay of timber components 10. Corrosion of fixings	1. Partially by scour protection and backfill replacement 2. No 3. Partially by scour protection 4. Partially by timber plank replacement 5. Partially by backfill replacement 6. Dependent on form of vandalism 7. Yes by scour protection works 8. Partially by timber plank replacement and treating timber 9. Partially by timber plank replacement and treating timber 10. Partly by repair/replacement of fixings

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Vertical walls (inc. with scour protection)	Gabion	Fluvial Coastal/ estuarine	1. Movement in or loss of surrounding supporting strata 2. Settlement 3. Undermining 4. Abrasion damage 5. Vandalism 6. Deformation of gabions 7. Corrosion and breakage of wires in gabions 8. Missing bricks/blocks or loss of fill material in gabions	1. Partially by scour protection 2. No 3. Partially by scour protection 4. Yes by rewiring of cages and replacing connecting wires 5. Dependent on form of vandalism 6. Yes by refill of gabion cages 7. Yes by repair/rewiring of gabion cages and replacing connecting wires 8. Partially by refilling gabion cages
Sheet piled structures	Anchored steel Cantilever steel	Fluvial Coastal/ estuarine	1. Movement in or loss of surrounding supporting strata 2. Settlement 3. Undermining 4. Corrosion of sheet piles or reinforcement including ALWC (Accelerated Low Water Corrosion) 5. Fatigue of steel 6. Chemical damage to timber piles 7. Insect damage, rot or decay of timber piles 8. Damage to structural components (e.g. tie-rod or anchorage system) 9. Abrasion damage 10. Evidence of leakage through or beneath the wall 11. Vandalism	1. Partially by scour protection and backfill replacement 2. No 3. Partially by scour protection 4. Partially by corrosion protection works 5. No 6. Partially by treating timber 7. Partially by treating timber 8. Partially through timely repair of any precursor damage to structural components 9. Partially by minor repair works 10. Possibly by minor repair works 11. Dependent on form of vandalism

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Demountable defences	Metal Wood	Fluvial	1. Support walls damaged or collapsed 2. Obstruction preventing deployment/erection 3. Anchorage points damaged or missing 4. Gaps present between elements 5. Corrosion/decay of elements 6. Seals missing or perished 7. Handling points damaged/missing	1. If repair feasible during maintenance works 2. If seen during maintenance inspections 3. If repair feasible during maintenance works 4. Closure of small gaps feasible on site 5. If replacement of parts feasible during maintenance works 6. If replacement of parts feasible during maintenance works 7. If replacement of parts feasible during maintenance works
Earth dykes or embankments	Varying core material, e.g. clay, shale With slope/toe protection or revetment	Fluvial Coastal/ estuarine	1. Movement in or loss of surrounding supporting strata 2. Settlement 3. Undermining 4. Lateral movement or sliding 5. Loss of fines due to seepage/infiltration 6. Cracking or fissuring 7. Shallow failures within slope 8. Crest or slope damage from animals, vehicles or people 9. Vegetation damage or loss 10. Erosion/scour of embankment 11. Evidence of seepage through or beneath the embankment 12. Vandalism 13. Damage to revetment/scour protection	1. No 2. No 3. No 4. No 5. Possibly by reducing cracking – vermin and vegetation control 6. Partially by vegetation and vermin control 7. No 8. Partially by vegetation and vermin control 9. No 10. No 11. Possibly by reducing cracking – vermin and vegetation control 12. Dependent on form of vandalism 13. No

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Sloping walls with slope protection or revetment	Turf	Fluvial Coastal/ estuarine	1. Movement in or loss of surrounding supporting strata 2. Settlement 3. Undermining 4. Lateral movement or sliding 5. Loss of fines due to seepage/infiltration 6. Cracking or fissuring 7. Shallow failures within slope 8. Crest or slope damage from animals, vehicles or people 9. Vegetation damage or loss 10. Erosion/scour of embankment 11. Evidence of seepage beneath the embankment 12. Vandalism	1. Partially by scour protection and backfill replacement 2. No 3. Partially by scour protection 4. Partially by scour protection 5. Possibly by reducing cracking – vermin and vegetation control 6. Partially by vegetation and vermin control 7. No 8. Partially by vegetation and vermin control and maintaining signage and fencing 9. No 10. Scour protection 11. Possibly by reducing cracking – vermin and vegetation control 12. Dependent on form of vandalism

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Sloping walls with slope protection or revetment	Permeable revetments Impermeable revetments	Fluvial Coastal/ estuarine	1. Movement in or loss of surrounding supporting strata 2. Settlement 3. Undermining 4. Lateral movement or sliding 5. Loss of fines due to seepage/infiltration 6. Cracking or fissuring 7. Shallow failures within slope 8. Crest or slope damage from animals, vehicles or people 9. Vegetation damage or loss 10. Erosion/scour of embankment 11. Evidence of seepage beneath the embankment 12. Vandalism 13. Damage to revetment/scour protection	1. Partially by scour protection and backfill replacement 2. No 3. Partially by scour protection 4. Partially by scour protection 5. Possibly by reducing cracking – vermin and vegetation control and replacement of missing/damaged elements 6. Partially by vegetation and vermin control 7. No 8. Partially by vegetation and vermin control and replacement of missing/damaged elements and maintaining signage and fencing 9. No 10. Scour protection 11. Possibly by reducing cracking – vermin and vegetation control and replacement of missing/damaged elements 12. Dependent on form of vandalism 13. by replacement of missing/damaged elements
Culverts – Pipe, box, arch	Concrete/ masonry/ brick Steel Plastic Clay	Fluvial	1. Deformation to culvert 2. Settlement to invert or soffit 3. Cracking, fissuring, or spalling of concrete or other components 4. Corrosion to elements 5. Missing bricks/blocks 6. Sealant or joint fill material loss 7. Vegetation growth inside culvert/root penetration	1. Partially by removal of silt 2. No 3. Partially by minor repairs, brickwork repair and sealant replacement 4. Partially by minor repairs 5. Partially by minor repairs and brickwork repair 6. Partially by sealant replacement 7. Partially by vegetation clearance and removal of silt

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Beaches with and without beach control structures (rock/timber groynes), offshore breakwaters (rock), breastwork (timber) and crib walls (timber)	Shingle/sand	Coastal/ estuarine	1. Continuous reduction in cross-sectional area or extent over long term 2. Extensive reduction in cross-sectional area or extent due to extreme event 3. Damage to control structures 4. Vegetation damage or loss on saltmarshes and dunes 5. Gulleying 6. Percolation through the beach 7. Third party damage, e.g. boat damage 8. Wind erosion	1. Possibly by maintenance renourishment/recycling. If large recharge required – cannot be addressed by maintenance renourishment/recycling – requires capital scheme 2. As (1) 3. See control structure maintenance 4. Possibly by beach renourishment/recycling 5. Possibly by beach renourishment/recycling 6. Possibly by removal of debris 7. Possibly by beach renourishment/recycling 8. Possibly by beach renourishment/recycling
Control structures	Rock groynes	Coastal	1. Voids in rock packing 2. Extents of loosely packed rock 3. Settlement of rock 4. Exposure of rock toe 5. Damage to exposed geotextile layer 6. Loss of rock armour or infill	1. Possibly through redistribution of rocks after heaving storm 2. Possibly through redistribution of rocks after heaving storm 3. No 4. Partially by scour protection 5. No 6. Partially by replacing damaged/eroded rocks
	Timber groynes	Coastal	1. Missing or damaged planks 2. Missing or damaged ties, walings and fixings 3. Groyne no longer able to arrest drift of beach material 4. Movement, rotation, bulging or undermining	1. Yes by replacing damaged/worn/missing planking 2. Yes by replacing damaged/worn/missing elements 3. Partially by recycling built-up material 4. Partially by recycling built-up material
	Offshore breakwaters (rock)	Coastal	1. Voids in rock packing 2. Extents of loosely packed rock 3. Settlement of rock 4. Exposure of rock toe 5. Damage to exposed geotextile layer 6. Loss of rock armour or infill	1. Possibly through redistribution of rocks after heaving storm 2. Possibly through redistribution of rocks after heaving storm 3. No 4. Partially by scour protection 5. No 6. Partially by replacing damaged/eroded rocks

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Dunes with or without holding structures		Coastal	1. Narrow or flat dune system 2. Damage or loss of vegetation 3. Low beach fronting dunes 4. Erosion or collapse of seaward dune slope 5. Evidence of overtopping, i.e. runnels 6. Damage to control structures 7. Third party damage, e.g. boat damage 8. Presence of foreign objects	1. Partially by installation of wind traps and sand fences, replanting/reprofiling 2. As (1) 3. As (1) 4. No 5. Partially by installation of wind traps and sand fences, replanting/reprofiling 6. No 7. No 8. No
Saltmarshes, saltings and warths with or without holding structures		Coastal/ estuarine	1. Steep and narrow slope 2. Erosion of marsh toe 3. Widening and lengthening of creek system 4. Vegetation loss or damage 5. Third party damage, e.g. grazing 6. Exposed underlying mud flat 7. Presence of foreign objects	All: No
Natural channel	Earth (e.g. regraded channel) Concrete	Fluvial	1. Overgrown vegetation 2. Instability in channel construction 3. Signs of sediment deposits 4. Trash deposits 5. Foreign objects present	1. By vegetation clearance activities 2. Partially by scour protection, vermin control, backfill replacement, etc 3. Partially by de-silting 4. By removal of debris from channel and banks 5. By removal of debris from channel and banks

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Weirs		Fluvial	1. Cracks, erosion or damage to crest, apron or wing walls 2. Uneven flow over crest 3. Sediment deposits on upstream face 4. Signs of erosion at structure sides/undermining 5. Loss of revetment at structure sides 6. Movement of abutments or wing walls 7. Vegetation encroachment 8. Evidence of leaching or water bypassing 9. Settlement 10. Blockwork or mortar missing	1. Partially by repairing damaged elements 2. Yes by repairing damaged elements 3. Yes by dredging upstream material 4. No – but yes by scour protection/backfill replacement 5. Partially through repair of damaged elements 6. Partially through repair of damaged elements (provide support) 7. Yes through vegetation clearance 8. Partially through repair of damaged elements 9. No 10. Partially by repair damaged elements
Outfalls		Fluvial Coastal	1. Pipe broken or blocked 2. Discharge outlet buried or blocked 3. Movement or settlement 4. Scour or undermining 5. Cracks in main structural elements 6. Broken timbers 7. Leaking pipe 8. Loss of thickness of piles due to corrosion, abrasion, etc 9. Fixings failing or missing	1. Partially by reactive obstruction removal 2. Partially by reactive obstruction removal 3. Partially by scour protection and replacement of backfill 4. Partially by scour protection 5. Partially by minor repair works 6. Partially by minor repair works 7. Partially by minor repair works and replacement of sealing 8. No – but possibly by corrosion control/protective coatings 9. Partially by minor repair works

Asset	Material	Environ-mental factors	Relevant deterioration processes for assets	Degree to which deterioration processes addressed by maintenance activity Note: 'Partially' identifies that the maintenance activity will not provide a solution for the deterioration process in every situation
Flap valves, penstocks and sluice gates		Coastal/ fluvial	1. Mechanism seized, operation compromised 2. Gate timbers rotten or missing 3. Flap has lost support, been damaged, has moved, is missing or is unable to operate 4. Corrosion, leakage, siltation or blockage 5. Damaged or missing mountings or fixings 6. Hinge bolts worn, corroded or missing 7. Siltation preventing operation 8. Deterioration of headwall	1. Partially by cleaning and repairing damaged elements and lubrication of moving parts 2. Partially by repairing damaged elements 3. Partially by repairing damaged elements 4. Partially by corrosion control, cleaning and replacing damaged elements and removing obstructions to flow of water 5. Partially by cleaning and repairing damaged elements 6. Yes by cleaning and repairing damaged elements 7. Partially by removing any obstructions to flow of water 8. Partially by repairing damaged elements
Debris screens		Fluvial	1. Corrosion of bars and fixing elements 2. Defects to bars, fixing or headwalls 3. Bar spacing distorted 4. Screen missing or not fixed correctly 5. Headwall missing 6. Mortar loss or surface spalling of headwall	1. Partially by minor repair works, bar replacement and fixing point repair 2. Partially by minor repair works, bar replacement and fixing point repair 3. Partially by minor repair works and bar replacement 4. Partially by fixing point repair and minor repair works 5. No 6. Yes by minor repair works and surface damage repair
Flood gates and barriers	Metal Wood	Coastal/ fluvial	1. Damage to or gaps in gate or barrier 2. Gate seals damaged, failed or missing 3. Locking mechanism damaged, seized or missing 4. Hinges difficult to operate 5. Distortion of gate or frame 6. Gate missing or obstructed 7. Cracking of concrete/brickwork	1. Yes by repairing damaged elements and replacement of components 2. Yes by repairing damaged elements and replacement of components 3. Yes by repairing damaged elements and replacement of components and lubrication of moving parts 4. Yes by repairing damaged elements and replacement of components and lubrication of moving parts 5. Partially 6. Partially 7. Yes

3.3.4 Understanding existing deterioration models

Various approaches are available for the construction of predictive deterioration and failure models. Their suitability for particular assets depends upon the availability of specific data relating to asset deterioration and failure, influencing factors (e.g. environment, material type/quality) and asset loading.

Common approaches include the following:

- trend analysis
- physical models
- failure event models
- condition models
- service lifetime (Weibull) models
- reliability (including Frangipol) models
- fragility models
- Markov chain models

Details of these methods are provided in Table 3.4 together with features relating to their application and their potential value for FCRM assets.

Note: Models that focus on both failure and deterioration are included in the table. A failure model relates the risk of asset failure (represented by a probability) to a loading parameter, which may then be used to calculate risk of failure over time. A deterioration model relates reduction in performance (represented by decreasing condition) to time.

Table 3.4 Deterioration models

Type	Description	Asset types/materials	Applicable to	Examples of software	Typical uses	Data input requirements	Outputs	Level of expertise required	Track record	Suitable for flood risk assets
Trend analysis, e.g. regression techniques	Data analysis (e.g. linear regression) to examine relationships between external factors and asset performance (failure model)	Any	Population	Models correlating burst rates of pipes with influencing factors (e.g. time, rainfall, temperature)	Estimating future failure trends for asset type	Failure data Data for influencing factors Asset characteristics (for cohorts)	Empirical equations for predicting performance/failure rates	Understanding of influencing factors required	Widely applied, e.g. burst models for pipe cohorts	Poor – unless failure data are available and influencing factors are well understood
Physical models, e.g. corrosion models	Asset observations (e.g. wall thickness/ pitting depth) used to assess progression of deterioration and to inform estimates of remaining life (deterioration model)	Assets made of materials indicated adjacent. Materials which experience progressive degradation over time, e.g. ferrous, cementitious	Individual asset + Population	Corrosion models for ferrous materials	Estimating remaining useful life of assets/cohort of assets (e.g. pipes)	Asset observations (e.g. wall thickness/pitting depth) Environmental factors (e.g. chloride content) Asset characteristics (for cohorts)	Prediction of asset observation based upon measured past trends, e.g. degradation/pitting rates (which can be linked to remaining service life)	Understanding of influence of asset observation on service life and asset failure	Widely applied to estimating remaining life of pipe networks/concrete structures Useful for designing concrete structures	Can be applied to ferrous or concrete structures (as appropriate)
			Individual asset + Population	Carbonation of concrete (BRE DG405)	Predictions of likely time to failure for reinforced concrete structures					
			Individual asset + Population	Alkali silica reaction in concrete (TRL CR177)	Predictions of likely time to failure for concrete/reinforced concrete structures					
			Individual asset + Population	Delayed ettringite formation: *in situ* concrete (BRE IP11/01)	Predictions of likely time to failure for concrete/reinforced concrete structures					
			Individual asset + Population	Modelling of Degradation, Dura Crete 1998 (Carbonation and chloride models, the consequences of corrosion)	Predictions of likely time to failure for concrete/reinforced concrete structures					
Failure event data models	Model uses historical failure event data to provide estimates of probability of failure. These are used to predict future failure trends (failure model)	Any asset group/ material with failure data	Population	*Ad hoc* failure models	Estimation of future asset failure rates based upon probabilistic methodology. Probability distribution is based upon past failures	Failure data Asset characteristics (for cohorts)	Prediction of asset failure rates	Understanding of probabilistic applications	Widely applied to assets where failure data are available	Poor – unless failure data are available and influencing factors are well understood
Condition models	Model based upon progression of asset through a set of condition grades (often with associated photographic guidance) (deterioration model)	Any	Individual asset + Population	Deterioration curves	Estimation of future condition grades based upon set of standard condition curves	Asset condition with age Influence of environment Influence of maintenance regime	Estimate of condition grade for asset	Understanding of effect of influencing factors on progression through condition grade	Widely applied, e.g. Environment Agency flood assets	Can be applied to wide range of assets. Requires data to build and calibrate the model
Service lifetime models, e.g. Weibull	Model uses service life data (historical, expert panel) to provide estimates of remaining service life. Based upon probabilities derived from historical records (failure model)	Any	Population	Weibull method	Mechanical & Electrical (M&E) assets	Service life data (failure data) Asset characteristics (for cohorts)	Prediction of asset remaining life, survival curves	Understanding of probabilistic applications Knowledge of typical asset service life	Widely applied to Mechanical & Electrical (M&E) assets where service life data are available	Can be applied to non-infrastructure assets
			Population	Service life prediction based on intelligent monitoring (CIRIA)	Concrete/reinforced concrete structures	Monitoring data Asset characteristics	Prediction of asset remaining life	Understanding of probabilistic applications Knowledge of typical asset service life	Limited	Possible application to concrete structures

Type	Description	Asset types/materials	Applicable to	Examples of software	Typical uses	Data input requirements	Outputs	Level of expertise required	Track record	Suitable for flood risk assets
Reliability models	Model uses mean time to failure (MTTF) and mean time to repair (MTTR) data to estimate reliability (failure model)	Electrical components Mechanical & Electrical (M&E) assets	Population	*Ad hoc* reliability models	Electrical components Mechanical & Electrical (M&E) assets	MTTF MTTR Asset characteristics (for cohort analysis)	Predictions of reliability and remaining service life	Understanding of reliability theory Understanding of asset failure	Widely applied to Mechanical & Electrical (M&E) assets where service life data are available	Can be applied to any asset group
	Model uses estimates of times to corrosion initiation derived from degradation equations to estimate time to failure (failure model)	Bridge decks/ reinforced concrete	Population	Reliability-based prediction of chloride ingress and reinforcement corrosion of ageing concrete bridge decks (NRCC-47011)	Ageing concrete bridge decks	Deterioration data Asset characteristics	Estimate of time to asset failure	Understanding of reliability theory Understanding of reinforcement corrosion processes	Limited	Can be applied to reinforced concrete structures
Frangopol type reliability models	Model assesses the reliability of the asset in terms of meeting its function (failure model)	Bridges	Population	Frangopol model	Bridges	Condition of assets Impact of failure	Model estimates how well the asset meets its structural needs	Understanding of reliability theory Understanding of failure impact	Evolving methodology	Can be applied to any asset group
Fragility curves	Model based upon condition inspections. These data are then used to develop fragility curves, which are used to forecast the number of years it takes for the asset to reach a critical condition (i.e. estimates probability of failure) (failure model)	Any	Individual asset + Population	PAMS (for Environment Agency) Floodsite RELIABLE	Used for flood defence assets (walls, embankments)	Asset condition deterioration curves Fragility curves Asset loading Asset characteristics (for cohorts)	Fragility curves	Understanding of deterioration curves Understanding of fragility curves	Used by Environment Agency for flood defence assets	Can be applied to any asset group
Markov chains	Visual-inspection based. Assumes deterioration 'jumps' in discrete phases. Assumed probability distribution (deterioration model)	Any assets where deterioration is not continuous (rather condition states may pass from one to a worse condition at unpredictable rates, without passing through each stage of the sequence) Typically – concrete, brick, masonry (e.g. sewers, bridges)	Population	Item Software's ITEM Toolkit (aeronautical) TreeAge Pro Healthcare University of Bristol's MLwiN Vose Software's ModelRisk	Large infrastructure – bridges, pavements, sewers and stormwater pipes Aeronautical	Asset condition Deterioration curves Asset characteristics (for cohorts)	Estimate of proportion of assets in a cohort in a particular condition grade (and hence estimate of remaining useful life)	Understanding of asset deterioration mechanisms	Widely applied to sewer condition profiling in water industry	Yes
			Population	PONTIS	Condition-based maintenance for bridges	Asset inventory data Condition inspections	Programme for bridge maintenance	Understanding of asset deterioration mechanisms	Widely applied to bridges in USA	Yes
			Population	BRIDGIT	Condition-based maintenance for bridges	Asset inventory data Condition inspections	Programme for bridge maintenance	Understanding of asset deterioration mechanisms	Widely applied to bridges in USA	Yes
			Population	SMIS (Structures Management Information Systems) (Highways) BridgeStation BMX (Bridge Management Expert)	Condition-based maintenance for bridges	Asset inventory data Condition inspections	Programme for bridge maintenance	Understanding of asset deterioration mechanisms	Used in UK	Yes

3.4 Development of generic deterioration modelling approach

3.4.1 Model selection

Each model approach set out in Table 3.4 was considered for its suitability for the present application, where tracking of deterioration trends and profiles is a primary requirement. Table 3.5 lists the conclusions of this exercise.

Table 3.5 Summary of deterioration models and their applicability to Environment Agency flood risk assets

Model type	Comments on suitability for flood defence assets (in the context of this project)	Model focus	Conclusion
Trend analysis	These models use historical data to identify failure event trends which are then extrapolated into the future. The absence of data relating to assets subject to different levels of maintenance would make the forward predictions unreliable. This model is not generally used for tracking determination trends	Asset failure modelling	Model tracks asset failure rather than asset condition/deterioration **Therefore not considered suitable in this context**
Physical models	The assets included on the study list are expected to deteriorate and fail through a number of mechanisms and modes. These are internal impacts (e.g. material) and external impacts (environment, loading). Since a combination of these factors are likely to have an influence, the application of physical models alone is considered to provide only a limited value to predicting deterioration	Asset deterioration and failure modelling	Model does not account for some key deterioration modes associated with these assets (e.g. wave loadings, ground movement) **Therefore not considered suitable in this context** Note: The general principles of materials deterioration will be applied in the construction of the models to validate and support other data
Failure event models	These models use historical data to define probability distributions to failure events. These distributions are then applied to the ageing asset stock into future periods. The absence of data relating to assets subject to different levels of maintenance would make the forward predictions unreliable	Asset failure modelling	Model tracks asset failure rather than asset condition/deterioration **Therefore not considered suitable in this context**

Model type	Comments on suitability for flood defence assets (in the context of this project)	Model focus	Conclusion
Condition models	Being based upon condition grades, which are used routinely for Environment Agency flood risk assets, this approach would be readily applicable. It is of note that Phase 1 of the project has already developed deterioration models based upon condition grades. The adoption of this approach would therefore offer considerable advantages	Asset deterioration and failure modelling, including end of asset life	Aligns well with previous methodology and data type and format in the NFCDD **Recommended for development in this project** The issue of the impact of maintenance needs to be addressed (see also text below)
Service lifetime (Weibull) models	These models use historical data or expert opinion to assign probability (e.g. Weibull) distributions to failure events and/or service lives. These distributions are then applied to the ageing asset stock into future periods. The absence of data and experience relating to assets subject to different levels of maintenance would make the forward predictions unreliable	End of asset life modelling (probability distributions)	Weibull models track end of life rather than asset deterioration **Therefore not considered suitable in this context**
Reliability (including Frangipol) models	These models rely on historical data (or expert opinion) to establish measures of past and predicted future reliability. The absence of data and experience relating to assets subject to different levels of maintenance would make the forward predictions unreliable	Asset reliability predictions	Could be applied but limited data linking condition with reliability would be a constraint **Therefore not considered suitable in this context**
Fragility models	Fragility models have been developed and widely applied to flood defence assets. They account not only for the asset condition, but also the loading upon an asset A model of this type can require complex analysis for application to individual assets The Environment Agency tool RELIABLE (Floodsite website http://www.floodsite.net/) is based upon this approach. This tool is focused on reliability of the asset in terms of probability of failure	Probability of asset failure	Fragility models are suitable for deterioration modelling in the particular context of predicting the probability of failure. The deterioration models required as outputs to the current project can be considered as 'precursor' models whose outputs could be used to inform input parameters for fragility models such as the Environment Agency RELIABLE tool **Therefore not considered suitable in this context**

Model type	Comments on suitability for flood defence assets (in the context of this project)	Model focus	Conclusion
Markov chain models	Markov chain models use the transitions of assets from one grade to another (worse) condition grade in the past to inform projections of behaviour into the future. The approach is generally applied to populations of assets rather than individual assets with results presented as a condition grade profile (i.e. proportion of the asset stock in each grade at a point in time)	Strategic assessment of trends in condition profile of asset population	Markov models are generally applied to a population of assets. They would not be appropriate for an individual asset, as required in this project **Therefore not considered suitable in this context** Note: Markov models could be applied to these assets in a strategic role to assess the condition profile of the asset stock and to assess overall investment budgets to manage asset serviceability

The model approach adopted will need to be informed by reliable data sources (e.g. condition grades, age of assets, asset characteristics – materials, location, design) and by expert opinion. It is noted that there is a general absence of models that are able to represent the impact of maintenance.

It can be seen from the above results that the preferred model approach which is most suited to further development in this project is a condition grade model. The reasons can be summed up as follows:

- Visual indicators used to assign condition grades are fully developed for all asset types covered by the present study (Environment Agency Condition Assessment Manual).
- Condition grades are routinely applied to Environment Agency flood defence assets, and models based upon these would be easily understood and would align with existing systems. This would facilitate take-up of the models by Environment Agency asset managers.
- Phase 1 of this project developed a series of deterioration curves based upon condition grades for a large sub-set of the study assets. The adoption of this approach would ensure continuity and would complement and build upon the technical developments and outputs from Phase 1 of the project.
- The impact of maintenance can be quantified through consideration of the impact of maintenance practices on the deterioration mechanisms (see Section 3.3.3) and through discussion with practitioners through consultation workshops.

3.4.2 Initial model development – maintenance regimes

With the condition grade modelling approach selected, the next step in model development was to define and standardise how maintenance is represented in the model. With this objective in mind a set of generic maintenance regimes has been established for application to all study assets. These are:

- Regime 1 – Low/basic maintenance regime: do minimum repair/maintenance (i.e. that required for H&S reasons, only replacing handrails is an example)
- Regime 2 – Medium maintenance regime
- Regime 3 – High maintenance regime

The levels of maintenance represented by these regimes will influence the rate of deterioration of an asset. Therefore a deterioration curve has to be developed for each maintenance regime. The deterioration curve serves to quantify the impact of the selected regime on the condition of the asset as indicated by the condition grade and in particular when grade transitions occur, e.g. deterioration from CG 3 to CG 4. Data derived from the various sources outlined in Section 3.2 have been used to construct the models for the three maintenance regime scenarios for each asset type. The workshop held on 18 April 2011 and attended by Environment Agency asset managers was also used to validate and explore the options proposed for the basis for the models and the underlying links between maintenance, refurbishment and asset deterioration.

It was noted above (Section 3.3.3) that the Environment Agency Maintenance Standards are aligned with target condition grades and identify activity levels to maintain assets at one of three options: CG 2, 3 and 4. These Environment Agency Maintenance Standards have been used as the basis for defining the three regimes within the deterioration model, with alignment as shown in Table 3.6.

Table 3.6 Maintenance regime and Environment Agency target condition grade alignment

Maintenance regime	Description	Environment Agency target condition grade alignment (equivalent to)
1	Low/basic	-
2	Medium	3
3	High	2

It would be the case that the higher the level of maintenance activity (and therefore higher maintenance costs) on any particular asset, the slower the rate of deterioration. This would lead to less frequent repair/refurbishment (and associated costs). A whole life cost tool, such as the prototype tested here, could be used in conjunction with calculated flood risk management system benefits from the SAMPs (System Asset Management Plans) IT system, or similar. It would allow additional uses, such as for optimising the selection of a maintenance regime for any asset or system.

Work schedules (activities and frequencies) have been defined for each regime and each asset. These are based upon the following generic maintenance types:

- Inspection and reactive repair (e.g. basic, H&S driven).
- Regular maintenance (as indicated in the maintenance standard aligned to the regime (see below)).
- Major repair/refurbishment at transition points in the deterioration trends (e.g. transition into CG 3 and into CG 4).
- Asset replacement at end of life (transition into CG 5).

The following work schedules are proposed for each regime. (Note: These schedules are generic for all assets.)

Regime 1: Low/basic – do minimum repair/maintenance

- Inspection + H&S repair (annually)
- Some major repair/maintenance at transition points into CG 3 and into CG 4
- Asset replacement at transition point into CG 5 – end of life

Regime 2: Medium maintenance regime

- Inspection + H&S repair (annually)
- Maintenance activities as proposed in the Environment Agency Maintenance Standards for maintaining at target CG 3 (Note: The maintenance standards will also pick up minor reactive repairs)
- Some major repair/refurbishment at transition points into CG 3 and into CG 4
- Increased frequency of maintenance at grade transition points
- Asset replacement at transition point into CG 5 – end of life

Regime 3: High maintenance regime

- Inspection + H&S repair (annually)
- Maintenance activities as proposed in the Environment Agency Maintenance Standards for maintaining at target CG 2 (Note: The maintenance standards will also pick up minor reactive repairs)
- Some major repair/refurbishment at transition points into CG 3 and into CG 4
- Increased frequency of maintenance at grade transition points
- Asset replacement at transition point into CG 5 – end of life

3.4.3 Initial model development – construction of deterioration model

Nine deterioration curves have been developed for each asset. These include the three different maintenance regimes (low, medium, high – see Section 3.4.2 above) and, for each of these maintenance regimes, three different environments/characteristics which influence likely deterioration rates:

- Slowest – arising from a sheltered location and/or high quality materials and construction, well-designed asset.
- Medium rate – considered a typical rate providing a mid-range value.
- Fastest – arising from an exposed location and/or poor quality materials/construction/design.

This makes a 3 x 3 matrix of potential deterioration scenarios for each asset (see Table 3.7).

Table 3.7 Potential deterioration scenarios

Maintenance regime	Likely deterioration rate		
	Slowest	Medium	Fastest
Low	X	X	X
Medium	X	X	X
High	X	X	X

Example deterioration curves are shown in Figure 3.1. This format represents deterioration of an asset under the three maintenance regimes (as above) but excluding major repair/refurbishment at grade transitions.

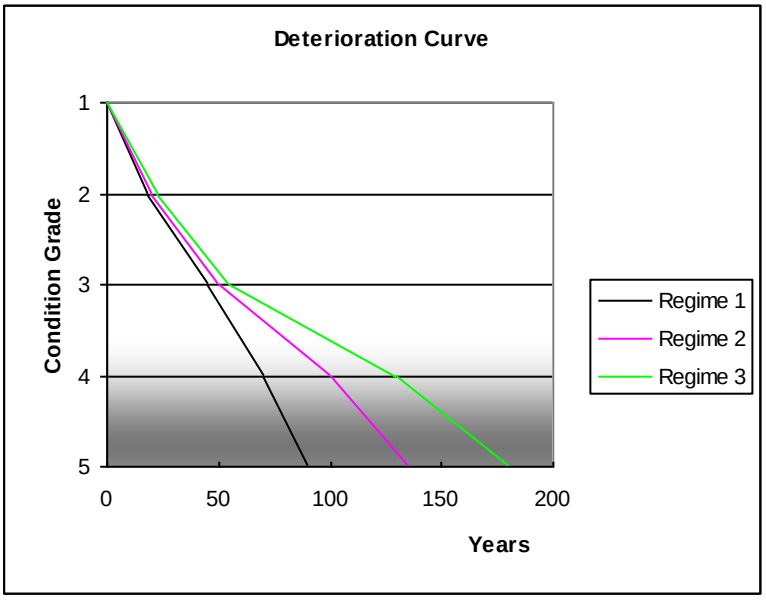

Figure 3.1 Example deterioration curve

As a consequence of the major repair/refurbishment included in the maintenance regimes at the transition points into CG 3 and CG 4, the simple deterioration curve as illustrated in Figure 3.1 is adjusted. This arises because of the improvement to the asset condition (and associated condition grade) on undertaking refurbishment.

The benefit of the refurbishment is expressed in the adjusted deterioration curves as a horizontal shift of the graph to the right, which represents a time delay in the commencement of further deterioration. The degree of adjustment is dependent upon three factors:

- The cost of the refurbishment (which is a surrogate for the scale of the improvement work) (expressed as a % of the replacement cost for the asset). The greater the % spend, the longer the time delay (i.e. greater benefit).
- The particular maintenance regime. For the same % spend the time delay increases in order regime 1, 2 and 3. This arises from the lower deterioration rate as the maintenance levels increase.
- The particular transition – whether to CG 3 or to CG 4. The delay is longer (i.e. refurbishment more beneficial) at the CG 3 transition; assumed to be so because the asset is in better overall condition at CG 3 compared to CG 4.

The actual time delay (years) is calculated as a % of the interval between CG 2 and CG 3 (for the transition at CG 3) and between CG 3 and CG 4 (for the transition at CG 4).

A matrix of values aligning % spend against benefits (as measured by time delay) for each maintenance regime/transition scenario has been developed for application in the whole life cost model. These values are shown in Table 3.8. It is to be noted that information to assist in model building of this type is not generally available. The data points were derived using expert judgement to set the framework for the spend:improvement relationships (i.e. the time

delays at 60% spend) with pro rata interpolation. This approach is considered to provide a reasonable approximation to actual situations.

Table 3.8 Adjustment to deterioration curves as a consequence of refurbishment

Regime 1		
Spend % of replacement cost	**Transition into CG 3**	**Transition into CG 4**
	Time delay % of interval CG 2 to 3	**Time delay % of interval CG 3 to 4**
0	0	0
5	11	8
10	22	17
15	33	25
20	43	33
25	54	42
30	65	50
35	76	58
40	87	67
45	98	75
50	108	83
55	119	92
60	130	100

Regime 2		
Spend % of replacement cost	**Transition into CG 3**	**Transition into CG 4**
	Time delay % of interval CG 2 to 3	**Time delay % of interval CG 3 to 4**
0	0	0
5	12	9
10	23	18
15	35	28
20	47	37
25	58	46
30	70	55
35	82	64
40	93	73
45	105	83
50	117	92
55	128	101
60	140	110

Regime 3		
Spend % of replacement cost	**Transition into CG 3**	**Transition into CG 4**
	Time delay % of interval CG 2 to 3	**Time delay % of interval CG 3 to 4**
0	0	0
5	13	10
10	25	20
15	38	30
20	50	40
25	63	50
30	75	60
35	88	70
40	100	80
45	113	90
50	125	100
55	138	110
60	150	120

The deterioration will continue at the original rate from this adjusted position. The consequence of this is an extension in asset life. The net result is shown in Figure 3.2.

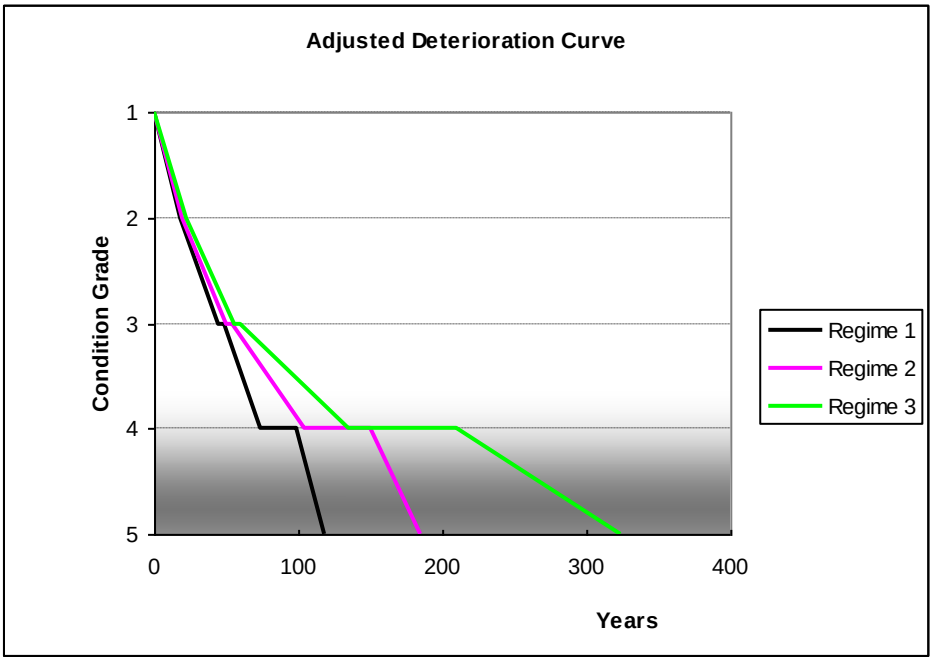

Figure 3.2 Example adjusted deterioration curve

The construction of the adjusted deterioration curve in this manner is an alternative to the 'saw-tooth' format often seen in published literature to demonstrate improvements arising from asset repair/refurbishment. Both representations are hypothetical approximations. In principle, the saw-tooth and horizontal shift (as in Figure 3.2) indicate the same general effect on the condition, i.e. a delay in further deterioration. The latter format is considered

equivalent to the saw-tooth with some of the detail not shown. This missing detail (indicative of the degree to which the condition grade is improved) is, in any case, not precisely known. It is therefore the case that the horizontal shift representation does not suggest a better understanding of the asset and the effect of investment on condition than actually exists.

The ability to restore condition would vary, being dependent on where in the life cycle the asset is, and very detailed asset information would be needed to build accurate models which could confidently illustrate the precise degree of condition grade improvement.

The composite curve shown in Figure 3.3 illustrates the approximate equivalence of the two representations. The adjusted horizontal shift curve is indicated by the red line, the additional detail provided by the saw-tooth curve is revealed by the blue line, which otherwise follows the profile of the red curve. It is evident that the general progression through the condition grade and the overall asset life is similar for both constructions.

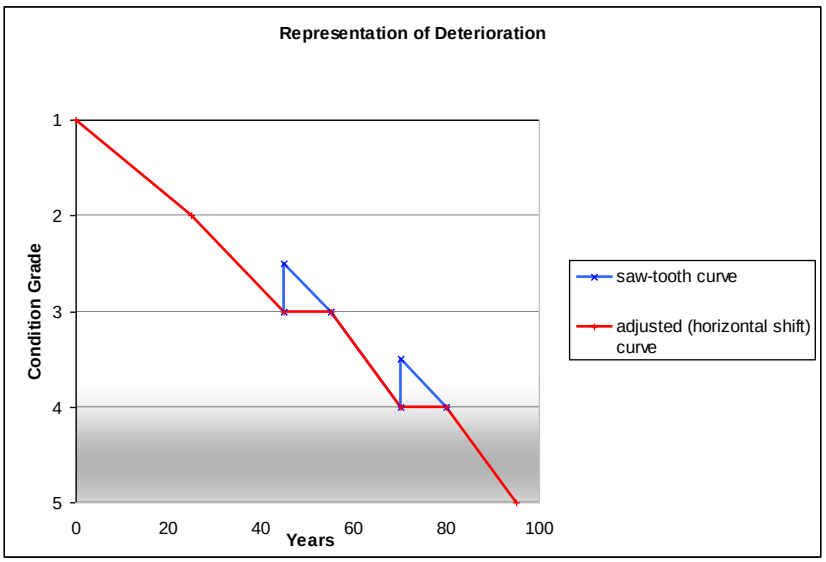

Figure 3.3 Comparison of the two deterioration curve representations

3.5 Development of individual deterioration models

3.5.1 Introduction

Deterioration models illustrate how the condition of the asset develops over time. The scale of maintenance activity, including type of maintenance work and frequency (as determined by the maintenance regime), will have an influence on the rate of deterioration. Similarly, the cost of maintenance activities over the life of the asset will be governed by the asset type and maintenance regime. The relationships between condition and costs have been defined through the construction of the deterioration models and the development of the prototype whole life cost tool.

The asset-specific deterioration curves are based upon information derived from numerous sources which enabled a review of the maintenance practices and their possible influence on asset condition.

3.5.2 Deterioration model data sources

Models were developed for the FCRM asset types listed in Table 2.1 above.

The source of the deterioration assessment data for each asset type is shown in Table 3.9.

Table 3.9 Deterioration model source data map

Asset class	Material	Environmental factors	Asset type (NFCDD database)	Deterioration curve based upon:					
				Phase 1 deterioration curve available	Phase 1 interviews	Phase 2 survey	Historical/ Halcrow experts	NFCDD data (age of asset vs condition grade)	Workshop 18 April 2011
Vertical walls (inc. with scour protection)	Concrete	Fluvial	Raised defence (man-made)	✓	✓	✓ (1 site)	✓	✓	✓
Vertical walls (inc. with scour protection)	Concrete	Coastal/ estuarine	Raised defence (man-made)	✓	✓	✓ (2 sites)	✓	✓	X
Vertical walls (inc. with scour protection)	Brick and masonry	Fluvial	Raised defence (man-made)	✓	✓	✓ (10 sites)	✓	✓	X
Vertical walls (inc. with scour protection)	Brick and masonry	Coastal/ estuarine	Raised defence (man-made)	✓	✓	✓ (18 sites)	✓	✓	✓
Vertical walls (inc. with scour protection)	Timber	Fluvial	Raised defence (man-made)	X	X	X	✓	✓	X
Vertical walls (inc. with scour protection)	Timber	Coastal/ estuarine	Raised defence (man-made)	X	X	X	✓	✓	X
Vertical walls (inc. with scour protection)	Gabion	Fluvial	Raised defence (man-made)	✓	✓	X	✓	✓	X
Vertical walls (inc. with scour protection)	Gabion	Coastal/ estuarine	Raised defence (man-made)	X	✓	X	✓	✓	X
Sheet piled structures	Anchored steel	Fluvial	Maintained channel	✓	✓	X	✓	✓	✓
Sheet piled structures	Anchored steel	Coastal/ estuarine	Raised coastal defence (man-made)	✓	X	X	✓	✓	X

Asset class	Material	Environmental factors	Asset type (NFCDD database)	Deterioration curve based upon:					
				Phase 1 deterioration curve available	Phase 1 interviews	Phase 2 survey	Historical/ Halcrow experts	NFCDD data (age of asset vs condition grade)	Workshop 18 April 2011
Sheet piled structures	Cantilever steel	Fluvial	Maintained channel	✓	✓	X	✓	✓	X
Sheet piled structures	Cantilever steel	Coastal/ estuarine	Raised coastal defence (man-made)	✓	X	X	✓	✓	X
Demountable defences	Metal	Fluvial	Raised defence (man-made)	X	X	X	✓	X	✓
Demountable defences	Wood	Fluvial	Raised defence (man-made)	X	X	X	✓	✓	X
Earth dykes or embankments	Varying core material, e.g. clay, shale	Fluvial	Raised defence (man-made)	✓	✓	✓ (16 sites)	✓	✓	X
Earth dykes or embankments	Varying core material, e.g. clay, shale	Coastal/ estuarine	Raised coastal defence (man-made)	X	✓	✓ (1 site)	✓	✓	X
Earth dykes or embankments	With slope/toe protection or revetment	Fluvial	Raised defence (man-made)	✓	✓	X	✓	✓	X
Earth dykes or embankments	With slope/toe protection or revetment	Coastal/ estuarine	Raised coastal defence (man-made)	✓	✓	X	✓	✓	X
Sloping walls with slope protection or revetment	Turf	Fluvial	Maintained channel	✓	✓	X	✓	✓	X
Sloping walls with slope protection or revetment	Turf	Coastal/ estuarine	Raised coastal defence (man-made)	X	✓	X	✓	✓	✓
Sloping walls with slope protection or revetment	Permeable revetments	Fluvial	Maintained channel	✓	✓	✓ (2 sites)	✓	✓	X

Asset class	Material	Environmental factors	Asset type (NFCDD database)	Deterioration curve based upon:					
				Phase 1 deterioration curve available	Phase 1 interviews	Phase 2 survey	Historical/ Halcrow experts	NFCDD data (age of asset vs condition grade)	Workshop 18 April 2011
Sloping walls with slope protection or revetment	Permeable revetments	Coastal/ estuarine	Raised coastal defence (man-made)	✓	✓	✓ (3 sites)	✓	✓	X
Sloping walls with slope protection or revetment	Impermeable revetments	Fluvial	Maintained channel	✓	✓	✓ (2 sites)	✓	✓	X
Sloping walls with slope protection or revetment	Impermeable revetments	Coastal/ estuarine	Raised coastal defence (man-made)	✓	✓	✓ (9 sites)	✓	✓	X
Culverts – pipe, box, arch	Concrete/ masonry/brick	Fluvial	Culverts Brick/concrete/stone/plastic/ ferrous/clay	✓	✓	X	✓	✓	X
Culverts – pipe, box, arch	Steel	Fluvial	Culverts Brick/concrete/stone/plastic/ ferrous/clay	✓	✓	X	✓	✓	X
Culverts – pipe, box, arch	Plastic	Fluvial	Culverts Brick/concrete/stone/plastic/ ferrous/clay	✓	✓	X	✓	✓	✓
Culverts – pipe, box, arch	Clay	Fluvial	Culverts Brick/concrete/stone/plastic/ ferrous/clay	✓	✓	X	✓	✓	X
Beaches with and without beach control structures (rock/timber groynes), offshore breakwaters (rock), breastwork (timber) and crib walls (timber)	Shingle/sand	Coastal/ estuarine		✓	✓	X	✓	✓	X
Control structures	Rock groynes	Coastal	Coastal erosion protection assets	X	✓	X	✓	✓	X
Control structures	Timber groynes	Coastal	Coastal erosion protection assets	X	✓	✓ (2 sites)	✓	✓	X

Asset class	Material	Environmental factors	Asset type (NFCDD database)	Deterioration curve based upon:					
				Phase 1 deterioration curve available	Phase 1 interviews	Phase 2 survey	Historical/ Halcrow experts	NFCDD data (age of asset vs condition grade)	Workshop 18 April 2011
Control structures	Offshore breakwaters (rock) Concrete	Coastal	Coastal erosion protection assets	X	✓	X	✓	✓	X
Control structures	Crib walls Breastwork	Coastal	Coastal erosion protection assets	X	✓	X	✓	✓	X
Dunes with or without holding structures		Coastal	Raised coastal defence (natural)	✓	✓	X	✓	X	X
Saltmarshes, saltings and warths with or without holding structures		Coastal/ estuarine		X	✓	X	✓	X	X
Natural (maintained) channel	Earth (e.g. regraded channel)	Fluvial	Maintained channel	X	✓	X	✓	✓	✓
Maintained channel	Concrete	Fluvial	Maintained channel	X	✓	X	✓	✓	X
Weirs		Fluvial	Flood defence structures	X	✓	X	✓	✓	X
Outfalls		Fluvial		X	✓	X	✓	✓	X
Outfalls		Coastal	Flood defence structures	X	✓	X	✓	✓	✓
Flap valves, moveable gates (penstocks and sluice gates)		Coastal/fluvial	Flood defence structures	X	✓	X	✓	✓	X
Debris screens		Fluvial	Flood defence structures	X	✓	X	✓	✓	✓
Flood gates and barriers	Metal	Coastal/fluvial		X	✓	X	✓	✓	✓
Flood gates and barriers	Wood	Coastal/fluvial		X	✓	X	✓	✓	X

The Phase 1 deterioration curves, where these existed, formed the basis of the revised model. The alignment of the Phase 2 asset list with Phase 1 models is shown in Table 3.10.

Table 3.10 Alignment of Phase 2 assets with Phase 1 deterioration curves

(Key: F = fluvial, C = coastal/estuarine)

Phase 2 asset list			Alignment with Phase 1 deterioration curves
Vertical walls	Concrete walls	F	Vertical wall concrete/brick/masonry fluvial
Vertical walls	Concrete walls	C	Vertical wall concrete coastal
Vertical walls	Brick and masonry walls	F	Vertical wall concrete/brick/masonry fluvial
Vertical walls	Brick and masonry walls	C	Vertical wall brick/masonry coastal
Vertical walls	Timber walls	F	None
Vertical walls	Timber walls	C	None
Vertical walls	Gabion walls	F	Vertical wall gabion fluvial
Vertical walls	Gabion walls	C	None (gabion wall fluvial considered)
Sheet piled structures	Anchored steel	F	Sheet piles fluvial
Sheet piled structures	Anchored steel	C	Sheet piles coastal
Sheet piled structures	Cantilever steel	F	Sheet piles fluvial
Sheet piled structures	Cantilever steel	C	Sheet piles coastal
Demountable defences	Metal	F	None
Demountable defences	Wood	F	None
Earth dykes or embankments	Varying core material	F	Turf embankment fluvial narrow and wide
Earth dykes or embankments	Varying core material	C	None (based on turf embankment fluvial narrow and wide)
Earth dykes or embankments	With slope/toe protection	F	Embankments rigid, rip-rap or flexible (fluvial) narrow and wide
Earth dykes or embankments	With slope/toe protection	C	Embankments permeable or impermeable revetments coastal
Sloping walls with slope protection or revetment	Turf	F	Turf embankment fluvial
Sloping walls with slope protection or revetment	Turf	C	None (based on turf embankment fluvial and permeable revetment coastal)
Sloping walls with slope protection or revetment	Permeable	F	None (based on embankment turf, rigid, rip-rap or flexible (fluvial))
Sloping walls with slope protection or revetment	Permeable	C	Coastal permeable (also used embankment, turf, rigid, rip-rap or flexible (fluvial))
Sloping walls with slope protection or revetment	Impermeable	F	None (based on embankment, rigid or flexible (fluvial))
Sloping walls with slope protection or revetment	Impermeable	C	Coastal impermeable (also used embankment rigid or flexible (fluvial))
Culverts	Concrete/masonry/brick	F	Culvert (range fast–slow covers materials)
Culverts	Steel	F	Culvert
Culverts	Plastic	F	Culvert
Culverts	Clay	F	Culvert
Beaches with and without control structures	Shingle/sand	C	Shingle
Control structures	Rock groynes	C	None

Phase 2 asset list			Alignment with Phase 1 deterioration curves
Control structures	Timber groynes	C	None
Control structures	Offshore breakwaters	C	None
Control structures	Breastwork (timber)	C	None
Control structures	Crib walls (timber)	C	None
Dunes with or without holding structures		C	Dunes
Saltmarshes, saltings and warths with or without holding structures		C	None
Maintained channels	Earth (e.g. regraded channels)	F	None
Maintained channels	Concrete/brick	F	None
Weirs		F	None
Outfalls		F	None
Outfalls		C	None
Flap valves		F	None
Flap valves		C	None
Moveable gates (penstocks)		F	None
Moveable gates (penstocks)		C	None
Moveable gates (sluice gates)		F	None
Moveable gates (sluice gates)		C	None
Debris screens		F	None
Flood gates and barriers	Metal	F	None
Flood gates and barriers	Metal	C	None
Flood gates and barriers	Wood	F	None
Flood gates and barriers	Wood	C	None

3.5.3 Development of model set

Appendix A provides details of the deterioration models for all assets under study.

3.6 Deterioration models – closing comments

This stage of the project has seen the development of a full set of deterioration curves for all assets on the study list. These curves provide predictive models to generate asset condition and performance profiles for future timeframes. They are suitable for use by asset managers and practitioners to assess the likely deterioration rates of the FCRM assets under three different levels of maintenance. They provide estimates of time to transition to the different condition states. These models have been integrated into the prototype whole life cost tool to illustrate how they could be used in a whole life context (see Section 4).

4 Whole life cost analysis

4.1 Whole life cost analysis – an introduction

4.1.1 What is whole life cost analysis?

ISO Standard 15686 Part 5 (referenced in Section 4.1.3 below) states that whole life costing is a 'methodology for systematic economic consideration of all whole life costs and benefits over a period of analysis, as defined in the agreed scope'. Whole life costing can consider the asset from its planning, through design, to end of life and include external costs, such as finance, business costs, income from land sale, user costs and similar.

The results of a whole life cost analysis provide the lowest cost option over the whole life of the analysis. It is then the decision of the asset manager, or owner, or key decision-maker, whether to go ahead with this option in light of the envisaged costs and benefits.

A whole life cost analysis is not necessarily always over the life of the asset; it can be shorter or longer. In the case of the current project, it is recommended that the whole life cost analysis is more of a fixed period, for example 100 years, in order to be able to capture at least one complete asset life cycle.

A brief review of three main methodologies or standards in UK asset management that cover whole life cost analysis are included in the next three sub-sections (4.1.2 to 4.1.4) and are taken from respectively:

- The Green Book methodology by HM Treasury
- BS ISO 15686 Part 5, Life Cycle Costing
- The Office of Government Commerce (OGC), Whole-life Costing

4.1.2 The Green Book

HM Treasury, *The Green Book: Appraisal and Evaluation in Central Government*, 2003

This book provides guidance on policy and project appraisal or evaluation for public sector organisations. It provides methodology on such issues as:

- creating options;
- estimating/valuing costs and benefits (including externalities, which are consequences of an economic activity that is experienced by unrelated third parties);
- distributional analysis (this analysis considers the distributional implications of each option; distributional could mean different groups or different locations);
- adjusting for relative price changes (i.e. expressing costs and benefits in 'real terms', or 'constant prices', i.e. at today's prices, as opposed to nominal terms);

it proposes that public sector organisations use the Social Time Preference Rate and Long-Term Discount Rate;

- risk and uncertainty – sensitivity analysis, scenario testing, Monte Carlo analysis;
- selecting the best option, using different methods – NPV (Net Present Value), benefit/cost ratio, IRR (Internal Rate of Return).

4.1.3 ISO Standard – Life Cycle Costing

BS ISO 15686-5:2008 *Buildings & Constructed Assets – Service Life Planning – Part 5: Life Cycle Costing*

This ISO provides definitions of terms relevant to whole life costing which accounts for costs incurred during all phases of a project including planning, design, construction, operation through to end of life, including all related costs (e.g. consultancy, project management, supervision and similar). Whole life cost analysis can help inform decisions for assets, and thus help with project, or asset, planning. For example, the results of the analysis can help inform decisions on choices between alternative designs for an asset, or evaluation of different investment scenarios (such as different maintenance strategies).

This standard discusses various issues involved in whole life cost analysis, such as types of data required, calculating cost variables, discounting, period of analysis and uncertainty and risk (including sensitivity analysis and Monte Carlo analysis).

4.1.4 OGC – Whole-life Costing

Office of Government Commerce, *Whole-Life Costing and Cost Management*, 2007

The Office of Government Commerce (OGC) is an office of HM Treasury. This guide explains how to manage costs through the life of a facility. This guide covers: establishing baseline costs, estimating whole life costs (including all the different costs – design costs, construction costs, maintenance, etc – that make up whole life costs), and cost management and reporting (financial planning, management of the risk allowance, etc).

4.2 Whole life cost tools: comparison and selection

A series of whole life cost tools was assessed for suitability for further development within the project. Each tool was assessed using a structured screening process which examined and scored each tool against a set of criteria.

The tools that were included in the screening process were:

- Environment Agency’s System Asset Management Plans (SAMPs)
- Environment Agency’s FCERM-AG Economic Appraisal tool
- Halcrow’s Cost Benefit Analysis (CBA) tool
- Halcrow’s Whole Life Cost (WLC) tool
- Halcrow’s HaLCAM (Halcrow Life Cycle Asset Management) tool

- Dundee University's Whole Life Cost Evaluator

Brief details of the tools are presented in Table 4.1.

Table 4.1 The whole life cost tools compared

Tool	Primary function	Asset level	Why tool included in comparison
SAMP	Whole life cost analysis of maintenance of Environment Agency flood defence assets	Environment Agency System[4] Major assets[5] individually	The tool is considered to provide a benchmark of current Environment Agency whole life cost capability for the maintenance of flood defence assets
FCERM-AG	Cost–benefit analysis (economic scheme appraisal)	Individual assets Scheme options	The tool is the Environment Agency's principal cost-benefit analysis tool for flood defence assets
Halcrow CBA	Cost-benefit analysis (scheme appraisal including benefits)	Asset portfolio Asset cohorts Individual assets Scheme options	Versatile tool: The tool is flexible and can be used to analyse different assets. It can include sensitivity and uncertainty analysis
Halcrow WLC	Whole life costing (scheme appraisal)	Asset portfolio Asset cohorts Individual assets Scheme options	Versatile tool: The tool is flexible and can be used to analyse different assets. It can include sensitivity and uncertainty analysis. Differs from Halcrow CBA tool in that it does not include assessment of benefits
HaLCAM	Whole life costing (timing/frequencies and costs of maintenance)	Asset portfolio Asset cohorts Individual assets	Whole life cost tool with track record in diverse industry sectors (buildings management, rail)
Dundee University Whole Life Cost Evaluator	Whole life costing (scheme appraisal)	Asset portfolio Asset cohorts Individual assets	Tool is non-Halcrow and non-Environment Agency. Provides means of comparison with tools from other sources (with possibly a different focus)

The screening process provided a ranked list of tools from which a short list of three (highest scoring) tools was prepared for further appraisal. These were:

- Halcrow's WLC tool
- Halcrow's HaLCAM

[4] A system is a group of assets which can be considered collectively to form an independent hydraulic unit providing flood protection to a defined area (Environment Agency definition).
[5] A major asset is a single identifiable asset or collection of assets on a site with (as a guide) a total estimated operating cost exceeding £5000 per year and either:

- a power source such as electricity, diesel, petrol, hydraulic, pneumatic, and so on, and/or
- it operates automatically, and/or
- it has a significant operator or public safety hazard arising from normal operation of the asset which requires specific management to achieve an acceptable risk.

Major assets include flood storage reservoirs (Environment Agency definition).

- Environment Agency's FCERM tool

Halcrow's WLC tool and the Environment Agency tool are both MS Excel based, while HaLCAM is a database tool, now written in Delphi language (although the data input form is in Excel).

These three whole life cost tools were subsequently tested for their suitability for application in the current project context. The conclusions reached were:

- Halcrow's WLC tool – easy to use, is flexible/robust. Requires some coding to make it more automated, which is readily achievable. Easy to link input data (such as size of assets) to the costs.
- Halcrow's HaLCAM tool – not suitable for the data for this project (without major modification of tool and/or data). This tool was therefore not considered further.
- Environment Agency's FCERM tool – easy to use. Manual data entry, but could include coding and data entry forms to make it more automated. Tool includes benefits (which could be hidden).

The assessment demonstrated that both Halcrow's WLC tool and the Environment Agency's FCERM tool are suitable for deriving reliable net whole life cost values. Table 4.2 presents a comparison of these two options.

Table 4.2 Comparison of tested whole life cost tools with key requirement criteria

Characteristic	Environment Agency's FCERM tool	Halcrow's WLC tool
Focus of analysis	Capital driven: • Project appraisal and optioneering • Primary objective to determine Benefit/cost ratio (BCR) and preferred policy options for flood or coastal erosion management units/asset systems • Assumptions regarding timing of works and maintenance are hidden (often developed elsewhere and conclusions fed into FCERM tool)	Capital and operational driven: • Project appraisal and optioneering • Maintenance programmes • Individual asset level • Clearly outlines relationship between condition grade and design life (in graphical representation) • Relationship between maintenance regime and whole life cost transparent • User can determine how changes in maintenance practices directly affect whole life cost
Modifications needed for project whole life cost data entry?	Modifications needed	Suitable immediately
Data entry	Manual	Automated via a data entry form
Asset level applicable	Management units Asset systems Scheme options	Asset portfolio Asset cohorts Asset systems Individual assets Scheme options
IT platform	MS Excel	MS Excel
Licence issues	None	None
Availability/accessibility of tool	No restrictions – existing Environment Agency tool	Tool to be handed over to the Environment Agency on completion of the Work Package
Robustness/flexibility	High	High

The FCERM tool is focused primarily on option appraisal and the economic (both costs and benefits) assessment of options to determine the economically preferred option for capital schemes. In contrast, the Halcrow WLC model can be used to focus more on the detail of how different maintenance assumptions and timings for intervention change the whole life cost. This is of particular benefit to asset managers, who require a clear understanding of how long-term spend may be affected by maintenance practices. Given the need for a flexible bespoke tool to be able to cope with the number of assets required for this project and other requirements such as deterioration of assets, it was felt that the Halcrow WLC model would be the most suitable tool for this project.

For these reasons, the decision was taken to proceed in this project with further development work on the Halcrow WLC tool.

The specification for the prototype whole life cost tool can be seen in Section 4.3 below.

4.3 Development of whole life cost profiles

4.3.1 Maintenance standards – existing Environment Agency standards

The Environment Agency Maintenance Standards report (*Delivering Consistent Standards for Sustainable Asset Management, FCRM Asset Management Maintenance Standards, Version 2*, March 2010) sets out maintenance practices and associated costs for approximately half of the assets included in the current study (see Table 4.3).

Table 4.3 Assets covered by the Environment Agency Maintenance Standards report

Asset class
Concrete walls
Brick walls
Steel walls (sheet piled structures)
Embankments
Culverts
Open channels (simple channels)
Open channels (engineered channels)
Outfalls
Debris screens

4.3.2 Extension of maintenance standards set

Maintenance standards for the remaining assets within the scope of the project Phase 2 (Table 2.1) were developed as part of this project phase using the same template. Table 4.4 lists these asset classes.

Table 4.4 Assets covered by maintenance standards developed as part of this study

Asset class
Timber walls
Gabion walls
Demountable defences – metal and wood
Sloping walls with slope protection or revetment
Beaches
Groynes (control structures)
Dunes
Saltmarshes
Weirs
Flap valves, penstocks and sluice gates
Flood gates and barriers

In the preparation of the new standards, the following were considered:

- Maintenance activities appropriate to the asset type
- Factors influencing unit costs
- Maintenance frequency and maintenance unit cost range
- Asset replacement value
- Asset replacement life

4.3.2.1 Maintenance activities

A list of maintenance activities for each type of asset was defined. These were derived from a number of sources:

- Review of existing standards to determine whether any of the practices described apply to other assets.
- The results of interviews with Environment Agency asset managers involved in the maintenance of these assets (these interviews were undertaken during Phase 1 of this project, see Environment Agency 2009, Appendix).
- Consultation with Halcrow's coastal and fluvial engineers.

The list of maintenance activities covers the majority of situations where each asset may occur. For each specific case it is unlikely that all of the maintenance activities will be required.

4.3.2.2 Factors influencing maintenance unit cost rate

Following the same process as used for the existing Environment Agency Maintenance Standards, a series of factors that could potentially affect the maintenance costs has been developed for each asset type. These factors are scored 0, 1 or 2, depending upon the degree to which they apply to the study asset. A weighting factor which reflects a perception of the extent to which the maintenance factor will affect the maintenance cost is then applied to the individual maintenance factor scores. The resulting individual weighted scores are then summed to give a total for the asset,

which is then applied to a cost range for the maintenance activities. This gives the relevant maintenance cost for the particular asset in its given environment and location. An example template is shown in Figure 4.1.

Figure 4.1 Example of 'Factors influencing maintenance costs' table

Factors influencing maintenance costs	Weighting factor	Score	Weighted score
Difficult access (e.g. site located far from a road, overhead power cables, protected sites, protected species etc.)	2		
Location known for excessive fly tipping	2		
Urban location with a greater requirement for reactive obstruction removal	1		
Invasive weeds	1		
Protected species may require a more sensitive environmental option, which should be decided in consultation with FRB	1		
		Total	

The user will give a score to each of the factors from 0 to 2 to describe how influential that factor will be at a specific site (0 = not applicable, 2 = highly relevant).

A table similar to that in Figure 4.1 has been drawn up for each asset type.

4.3.2.3 Maintenance frequency and maintenance unit cost range

A high and low estimate of the maintenance cost for each asset for target CG 2, 3 and 4 have been provided within the maintenance standards. On applying the standard to a specific asset, the sliding scale described in Section 4.3.2.2 is used to determine where in the cost range the asset fits. Where correspondence between asset types was evident, the same costs outlined in the current Environment Agency Maintenance Standards were used to maintain a standard approach throughout. Where this information was not available, information was sourced from Halcrow Engineers and specialists experienced with these asset types.

The frequency required for each maintenance activity has also been provided, for each target condition. Information was obtained from the following sources:

- Interviews with Environment Agency asset managers involved with maintenance activities on these assets (Phase 1 of this project).
- Workshop activities on 18 April 2011.
- Halcrow specialists.

The maintenance standards that have been developed during this project can be found in Appendix B.

4.3.2.4 Asset replacement value

A number of sources were consulted to produce a range of asset replacement costs for each asset. These are presented in Table 4.5. Where necessary, the cost rates have been updated to 2010 using the Office for National Statistics' Consumer Price Indices (CPI, http://www.statistics.gov.uk/statbase/Product.asp?vlnk=868).

The asset replacement values, together with the source of the data and factors affecting the cost rate, are presented in Appendix C.

Table 4.5 Sources of information for asset replacement values

Source	Description	Comments
Environment Agency's *Flood Risk Management Estimating Guide – Unit Cost Database 2007*	This publication is provided to Environment Agency project managers to give a source of cost estimating data. It was developed based on information from 300 Environment Agency capital projects	– A useful source of costing information for flood risk management – Costs presented are 2007 prices – No distinction made in this handbook between differing costs for different construction materials (i.e. timber revetment vs. concrete) – Does not cover all types of asset – Contains some assets that are not covered in the 2010 update
Environment Agency's *Flood Risk Management Estimating Guide – Update 2010*	An update of the 2007 Unit Cost Database, now contains data from 450 Environment Agency capital projects	– Up-to-date costing provided in this revision – Does not cover all assets included in this project
Halcrow Costs Database	A database of coastal and fluvial defence cost estimates based on previous Halcrow projects and experience	– A database of costs used on Halcrow projects in recent years – Some costs are project specific
Coastal strategies and projects (various)	Data have been drawn from various projects conducted by Halcrow Group Ltd to derive costing information, e.g. Arun to Adur Strategy 2007, Aldeburgh Coast and Estuary Study 2010, etc.	– Costs are project specific but provide a good range of costs and different scenarios for each asset
NFCDD	A 2010 download of the NFCDD database was analysed to derive costs and asset lives for as many types of asset as possible	– Methods of deriving costs are unknown – Dates of costs are unknown (so cannot be subject to inflation) – Dimensions of the defences in question are often not given – Searches have been made for specific words in NFCDD; there may be significantly more information available but this would require a more detailed, more time-consuming study – In summary, the NFCDD data are of unknown provenance and may be highly variable in reliability for use in this context
Internet search for information	The Construction Information Service online database was searched for asset construction costs	– Very little costing information supplied in any of these sources – Information obtained from these sources has been considered to be low confidence
Scottish Natural Heritage (2000) – *A Guide to Managing Coastal Erosion in Beach/Dune Systems*	This guide identifies best practice for managing coastal erosion in beach/dune systems	– Cost information supplied for a number of asset types – Costs were specified for the year 2000

A range of asset replacement values has been derived for each asset, per kilometre of asset (for hard defences) or per cubic metre of material (for rock defences and beaches). These costs take into account the varying factors affecting construction of a new asset.

4.3.2.5 Asset replacement life

The design life for each asset is often stipulated as a design criterion during the design phase of the scheme. The design life of a structure is limited by a number of factors, including the construction materials used, and assumptions are often made regarding the level of maintenance to be provided for that asset throughout its life. Under a 'do nothing' scenario, the duration of an asset's life will vary according to a large number of factors, including asset exposure, size, construction type, etc. As asset failure is rare, little information is available to define these figures.

The HR Wallingford (2003) *Whole Life Costs and Project Procurement in Port, Coastal and Fluvial Engineering* report was used to provide guidance on the expected lifetime of structures based on British Standards (BS 6349) recommendations. These figures together with the conclusions of consultation with experts within Halcrow have been used to estimate asset life durations for the 'do nothing' scenario.

This information has been used in construction and validation of the deterioration curves described above (Section 3).

4.3.3 Development of whole life cost profiles

The whole life cost profiles have been derived using the following primary sources of information:

- Maintenance standards – developed for all the study assets and which define maintenance activities and their frequencies (along with a cost range), to maintain the asset to a particular condition grade.
- Deterioration curves – (as discussed in Section 3 above).The deterioration curve is used to identify the points at which major maintenance and replacement occur for a particular asset.

Maintenance regimes and their impact on asset deterioration (as represented by deterioration curves) were introduced in Sections 3.4.2 and 3.4.3 above. The following sections discuss these in the context of whole life cost profiles.

4.3.3.1 Deterioration curves – basis for whole life costs

The deterioration curves provide time 'anchors' for each asset type in terms of asset life and transitions between condition grades.

The following is an example of vertical walls – sheet piles, in a coastal environment, to illustrate the concept.

Table 4.6 and Figure 4.2 illustrate the transition, or anchor points, i.e. the asset ages when, on average, an asset of the type indicated is deemed to pass from one condition grade to another (worse) grade (e.g. transition from CG 2 to CG 3 or from CG 3 to CG 4). These points in time can be considered 'triggers' indicating a need for some capital maintenance to take place, to upgrade the asset. For example, when the asset reaches CG 4, maintenance work would be needed to bring it back to CG 3 or better.

Table 4.6 Transition years between condition grades – example based upon vertical walls – sheet piles

Years to grade transitions for	Condition grade				
	1	**2**	**3**	**4**	**5**
Maintenance Regime 1	0	8	30	43	50
Maintenance Regime 2	0	8	35	53	60
Maintenance Regime 3	0	8	40	63	70

Note: The transition times (in years) have been derived for the three maintenance regimes – 1, 2 and 3, with increasing levels of maintenance activity respectively (introduced above – Section 3.4.2 – with further detail below (see Section 4.3.3.2)).

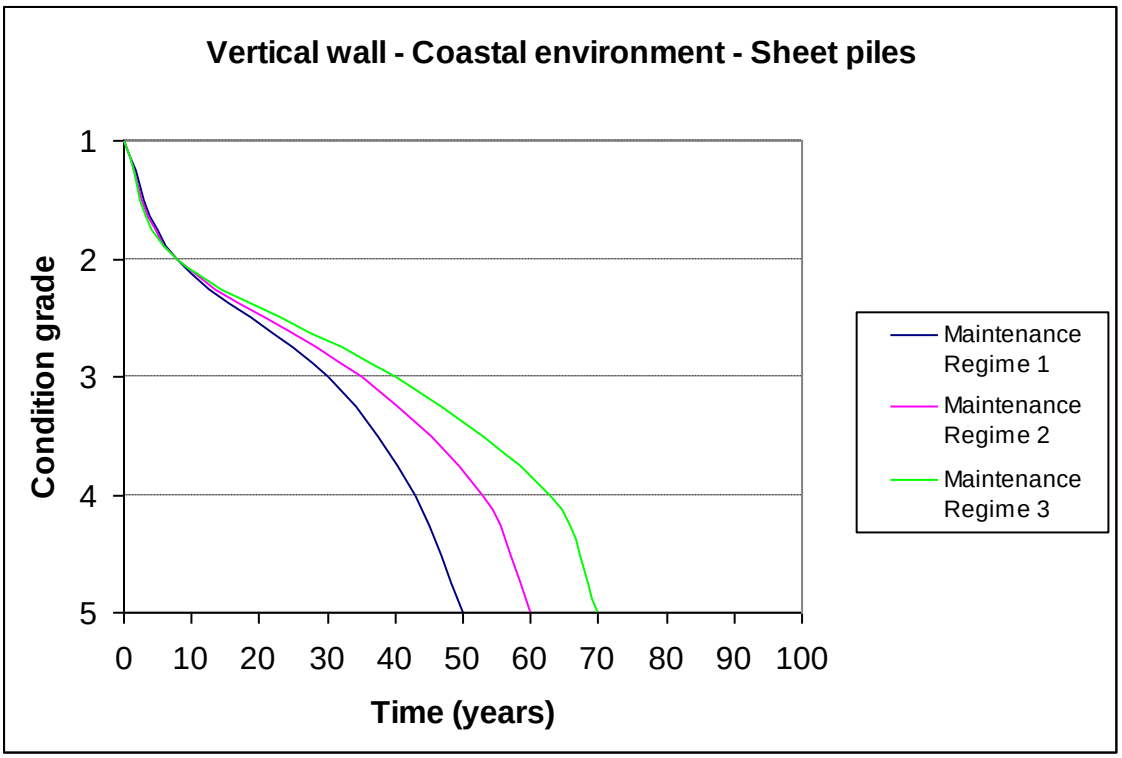

Figure 4.2 Deterioration curve for vertical wall – sheet piles

4.3.3.2 Maintenance regimes for whole life cost analysis

As indicated above, a set of generic maintenance regimes has been established for application to all assets. These are (see Table 4.7):

- Regime 1 – Low/basic maintenance regime: do minimum repair/maintenance (i.e. that required for H&S reasons only, replacing handrails is an example)
- Regime 2 – Medium maintenance regime
- Regime 3 – High Maintenance regime

Table 4.7 Maintenance regime and target condition grade alignment

WLC Maintenance Regime	Description	Environment Agency target condition grade alignment (equivalent to)
1	Low/basic	Not applicable
2	Medium	3
3	High	2

It is to be noted that the Environment Agency Maintenance Standards are aligned with target condition grades and identify regimes to maintain assets at one of three options: CG 2, 3 and 4, denoted high, medium and basic respectively. The maintenance standards for the Environment Agency target condition grades have been used to define activity levels for the maintenance regimes within the WLC model (see Table 4.7). As previously noted, it cannot be assumed that an asset can be kept at a specific condition grade indefinitely (i.e. over the whole life cost horizon). Despite ongoing maintenance there will be some deterioration and change to condition grade. Currently, the three maintenance regimes are 'mapped' to the Environment Agency Maintenance Standards, rather than adopting the assumption that an asset can be maintained in, for example, CG 2, indefinitely.

To set up the whole life cost spreadsheets, work schedules (activities and frequencies) are defined for each regime and each asset. The following information is used to define the whole life cost profiles:

- Asset life under the three maintenance regimes (equivalent to point representing transition to CG 5).
- Time in service at each transition between condition grades (1 to 2, 2 to 3, etc) for each maintenance regime (taken from the deterioration curves).
- Environment Agency Maintenance Standards plus inspection/reactive repair models (see below).

The following work schedules are proposed for each regime. (Note: For ease of illustration and completeness, the regimes set out below are applicable to assets as they age from their construction date. The WLC tool has been developed to accommodate analysis of existing assets beginning at their current age and condition.)

Regime 1: Low/basic – do minimum repair/maintenance – refer to appropriate deterioration curve

These schedules are generic for all assets.

- An allowance for inspection + H&S repair (annually). Input – an annual cost over time horizon of analysis.
- Some major repair/refurbishment at transition points into CG 3 and into CG 4. Associated costs will be a percentage of replacement cost as provided in Appendix C. Note these values are user defined (from a selection of values (0 to 60% with 5% intervals) – see Section 3.4.3 and Table 3.8). Input – costs incurred equivalent to % figures at the two transition (anchor) points.
- Asset replacement at transition point into CG 5 – end of life. Input – full replacement costs to be incurred at end of life.

Table 4.8 Proposed maintenance frequencies and costs for Regime 1

Activity	Frequency/in year number	Cost
Inspection and reactive H&S work	Annual	Cost for linear or point asset (see Section 4.3.3.3 below)
Maintenance activities	Not applicable to Regime 1	Not applicable
Major repair/refurbishment into CG 3	Determined by deterioration curve^	% of replacement cost*
Major repair/refurbishment into CG 4	Determined by deterioration curve^	% of replacement cost*
Replacement (at transition to CG 5)	Determined by deterioration curve^	Full replacement cost
* % figures are user-selected from the range 0 to 60% in 5% intervals ^ plus repeat as necessary in time horizon (see Note below)		

Note: For all regimes, if the time horizon of the whole life cost analysis exceeds asset life, deterioration of the new asset will begin again with the same activities in a cyclic fashion (i.e. it may be the case that the asset is replaced more than once in the time horizon of the analysis).

Regime 2: Medium maintenance regime – refer to appropriate deterioration curve

Note these are again generic (see note above under Regime 1):

- An allowance for inspection + H&S repair (annually).
- Maintenance activities as proposed in the maintenance standards for maintaining at target CG 3 (Note: The maintenance standards will pick up minor reactive repairs).
- Some major repair/refurbishment at transition points into CG 3 and into CG 4. Associated costs will be a % of replacement cost as provided in Appendix C. Note these values are user defined (from a selection of values (0 to 60% with 5% intervals) – see Section 3.4.3 and Table 3.8). Input – costs incurred equivalent to % figures at the two transition (anchor) points.
- Increase frequency of maintenance at transition/anchor points (to deal with this in the model, an increase can be applied to maintenance cost of x% – value of x to be user defined, default values provided).
- Asset replacement at transition point into CG 5 – end of life.

Table 4.9 Proposed maintenance frequencies and costs for Regime 2

Activity	Frequency/in year number	Cost
Inspection and reactive H&S work	Annual	Cost for linear or point asset
Maintenance activities (proactive)$	Annual	Maintenance cost to maintain target CG 3
Major repair/refurbishment into CG 3	Determined by deterioration curve^	% of replacement cost*
Major repair/refurbishment into CG 4	Determined by deterioration curve^	% of replacement cost*
Replacement (at transition to CG 5)	Determined by deterioration curve^	Full replacement cost
* % figures are user-selected from the range 0 to 60% in 5% intervals ^ plus repeat as necessary in time horizon (see Note above) $ Maintenance frequency increased at grade transitions (into CG 3 and into CG 4). Default values equivalent to increase of 5 and 10% annual costs		

Regime 3: High maintenance regime – refer to appropriate deterioration curve

Note these are again generic (see note above under Regime 1).

- An allowance for inspection + H&S repair (annually).
- Maintenance activities as proposed in the Maintenance Standards for maintaining at target CG 2 (Note: The maintenance standards will pick up minor reactive repairs).
- Some major repair/refurbishment at transition points into CG 3 and into CG 4. Associated costs will be a % of replacement cost as provided in Appendix C. Note these values are user defined (from a selection of values (0 to 60% with 5% intervals) – see Section 3.33 and Table 3.8). Input – costs incurred equivalent to % figures at the two transition (anchor) points.
- Increase frequency of maintenance at transition/anchor points (to deal with this in the model, an increase can be applied to maintenance cost of x% – value of x to be user defined, default values will be provided).
- Asset replacement at transition point into CG 5 – end of life.

Table 4.10 Proposed maintenance frequencies and costs for Regime 3

Activity	Frequency/in year number	Cost
Inspection and reactive H&S work	Annual	Cost for linear or point asset
Maintenance activities (proactive)$	Annual	Maintenance cost to maintain target CG 2
Major repair/refurbishment into CG 3	Determined by deterioration curve^	% of replacement cost*
Major repair/refurbishment into CG 4	Determined by deterioration curve^	% of replacement cost*
Replacement (at transition to CG 5)	Determined by deterioration curve^	Full replacement cost
* % figures are user-selected from the range 0 to 60% in 5% intervals ^ plus repeat as necessary in time horizon (see Note above) $ Maintenance frequency increased at grade transitions (into CG 3 and into CG 4). Default values equivalent to increase of 5 and 10% annual costs		

Cost data are included for all asset types to enable application of the generic models to specific assets.

As an illustration of the application of these maintenance regimes to flood management assets, Tables 4.11 and 4.12 list activities, costs and frequencies applicable to two example assets (brick walls (linear assets) and debris screens (point assets)). (Note: For the purposes of estimating costs some assumptions have been made regarding asset size (and other influencing characteristics) – refer to Tables 4.13 and 4.14 below.) Information relating to the derivation of the cost data is included in Section 4.3.3.3 below.

Table 4.11 Example of maintenance regimes – brick wall (assumes 100 year time horizon)

Class of activity	In year number	Cost	In year number	Cost	In year number	Cost	Typical activities (degree depends upon maintenance regime)	How estimated
Brick wall example	**Regime 1**		**Regime 2**		**Regime 3**			
Inspection and reactive H&S work	All	£1,667	All	£1,667	All	£1,667	Inspection and repair to make asset safe (e.g. removal of loose components, replacement of signs)	Calculated (see Section 4.3.3.3)
Maintenance activities	None	N/A	All	£120	All	£160	Vegetation clearance, minor wall repairs (replacement of missing bricks, re-pointing), replacement of backfill	From Environment Agency Maintenance Standard applicable to target CG 2 (for Regime 3) and target CG 3 for Regime 2. These costs will increase at transition points into target CG 3 and CG 4
Major repair into grade 3	50	£4,000	60	£3,200	70	£ 2,000	Partial rebuilding	% of asset replacement costs (these are user defined, examples shown)
Major repair into grade 4	70	£10,000	100	£6,000	130	£4,000	Partial rebuilding	% of asset replacement costs (these are user defined, examples shown)
Replacement	90	£40,000	120	£40,000	150	£40,000	Complete asset replacement	Asset replacement value (see Appendix C)

Table 4.12 Example of maintenance regimes – debris screens (assumes 100 year time horizon)

Class of activity	In year number	Cost	In year number	Cost	In year number	Cost	Typical activities (degree depends upon maintenance regime)	How estimated
Debris screens example	**Regime 1**		**Regime 2**		**Regime 3**			
Inspection and reactive H&S work	All	£833	All	£833	All	£833	Inspection and repair to make asset safe (e.g. repair of fencing, replacement of signs)	Calculated (see Section 4.3.3.3)
Maintenance activities	None	N/A	All	£1,000	All	£1,620	Obstruction removal, vegetation clearance, screen/headwall repair (minor), fixing repair	From Environment Agency Maintenance Standard applicable to target CG 2 (for Regime 3) and target CG 3 for Regime 2. These costs will increase at transition points into target CG 3 and CG 4
Major repair into CG 3	15 & 55	£2,000	20 & 70	£1,600	25 & 85	£1,000	Component replacement, part rebuilding of headwall	% of asset replacement costs (these are user defined, examples shown)
Major repair into CG 4	25 & 65	£5,000	35 & 85	£ 3,000	45	£2,000	Component replacement, part rebuilding of headwall	% of asset replacement costs (these are user defined, examples shown)
Replacement	40 & 80	£20,000	50 & 100	£20,000	60	£20,000	Complete asset replacement	Asset replacement value (see Appendix C)

The information in Tables 4.13 and 4.14 is collated and presented for the purpose of explaining the cost illustrations in Tables 4.11 and 4.12. Assumptions relating to asset class, size and location were made in order to provide a typical asset; cost information was then derived from the respective maintenance standard.

Table 4.13 Assumed data on the linear asset (brick wall)

Question	Response
Asset class	Walls
Asset material	Brick
Asset configuration	Linear
Length of asset (km)	0.2
Unit replacement cost per km	£200,000
Replacement cost	£40,000
Manual or mechanical vegetation clearance[6]	Mechanical
Length grouping[7]	> 50 m up to 500 m

Table 4.14 Assumed data on the point asset (debris screen)

Question	Response
Asset class	Debris screens
Asset material	N/A
Asset configuration	Point
Replacement unit cost	£20,000
Manual or mechanical vegetation clearance	Manual
Urban or woodland location	Woodland

4.3.3.3 Costs for whole life cost models

The costs required for the whole life cost models are:

- Inspection and reactive H&S work costs
- Maintenance costs
- Refurbishment costs
- Replacement costs

The actual costs are asset specific. The methodology used to estimate/calculate the costs provided in the model is described below. However, the WLC tool has the functionality to enable the user to overwrite all of these default costs, if desired.

1. Costs for inspection and reactive H&S work

Two different models have been built for inspection and reactive health and safety (H&S) work costs, to deal separately with point assets and linear assets.

Point assets cover:

- weirs
- flap valves, etc
- flood gates and barriers
- outfalls
- debris screens

[6] As in the maintenance standards.
[7] Required to derive the appropriate inspection costs; see Section 4.3.3.3.

Cost per annum for reactive work for point assets are estimated as shown in Table 4.15 and the following text.

Table 4.15 Proposed methodology to calculate reactive repair costs

Number of man-days per repair	X
Cost per man-day	£250 (Environment Agency figure)
Total staff cost per repair	£250 * X
Cost of consumables	2/3 * staff costs (Note: Environment Agency give 60:40 staff:consumables split for maintenance work)
Total cost per repair	Sum total staff + consumables costs
Frequency per annum	Y
Cost of reactive repairs per annum	Y * total cost per repair

Source for man-day cost and staff:consumables split: *Environment Agency 2005.*

Typical values for X and Y have been derived for all point assets through evaluation of likely activities.

Linear assets cover sea/flood walls, embankments, culverts and similar.

Cost per annum for reactive work is estimated in the same way as above for four asset classifications (which have been developed to account for the specific scaling issue of asset length associated with assets of this type and the impact on costs):

1. Assets up to and including 20 m in length.
2. Assets > 20 m and up to and including 50 m in length.
3. Assets > 50 m and up to and including 500 m in length.
4. Assets > 500 m in length.

The four classifications enable the longer assets to be assigned more man-days and consumables. Values for X will be different for the four categories (increasing in order 1 to 4). Y may be the same for all four categories. Typical values for X and Y have been defined for all linear assets.

2. Costs for maintenance work – as defined in maintenance standards

The maintenance standards outline the costs for maintenance. These standards present a scoring procedure in order to position costs for specific assets on a scale of low to high. Scoring criteria relate to asset-specific attributes, e.g. access limitations, asset location, size, aggressive environment and similar.

As described above, the maintenance regimes which include regular maintenance activities (Regimes 2 and 3) have been aligned to maintenance standards (as defined by target condition grade) (see Table 4.7 above). The costs from the particular maintenance standards (for the particular asset) have been used in the model.

Maintenance Regimes 2 and 3 also include the introduction of increased frequency of maintenance at transition/anchor points (as defined by the deterioration curves): the tool deals with this by increasing the annual maintenance costs by a percentage (rather than increasing frequency), when the asset reaches CG 3, and by a further percentage on these new maintenance costs when the asset reaches CG 4. Default values of 10% and 20% respectively are installed but the user can change these percentages if desired.

3. Costs for refurbishment

Refurbishment costs are a percentage of replacement cost, with default values provided which can be overwritten by the user. The model allows for refurbishment to

occur when the asset reaches transition points at CG 2 to CG 3 and CG 3 to CG 4 (as defined by the adjusted deterioration curve (Section 3.4.3)). This refurbishment is a major repair which assumes partial replacement of the asset to a proportional degree equivalent to the % value assigned.

4. Costs for replacement

Replacement costs for each asset type have been estimated based on a number of databases and engineering knowledge and previous projects (see Table 4.5 above and the References section of the report). For each asset type, a unit replacement cost (£/m or £/km), or a range of unit costs representing the range in size of asset (e.g. seawall height), has been derived. The same scoring system used for maintenance costs estimation is also used to identify which cost within the range provided is applicable to a specific asset.

The expected asset life per maintenance regime (i.e. when it reaches CG 5) is identified by the deterioration curve 'anchor' transition CG 4 to CG 5.

4.3.3.4 Exposure and quality considerations relating to whole life cost profiles

The deterioration curves provide three deterioration rate scenarios: slowest, medium rate and fastest, which are determined by the specific exposure and quality conditions which apply to the asset, as follows:

- Slowest deterioration rate – arising from a sheltered location and/or high quality materials and construction, well-designed asset.
- Medium deterioration rate – considered a typical rate providing a mid-range value representing an average situation, with assets being neither exposed nor sheltered.
- Fastest deterioration rate – arising from an exposed location and/or poor quality materials/construction/design.

The explanation below shows how these three scenarios are used in the WLC tool.

Figure 4.3 illustrates the variation in deterioration, with an example of masonry/brick culverts.

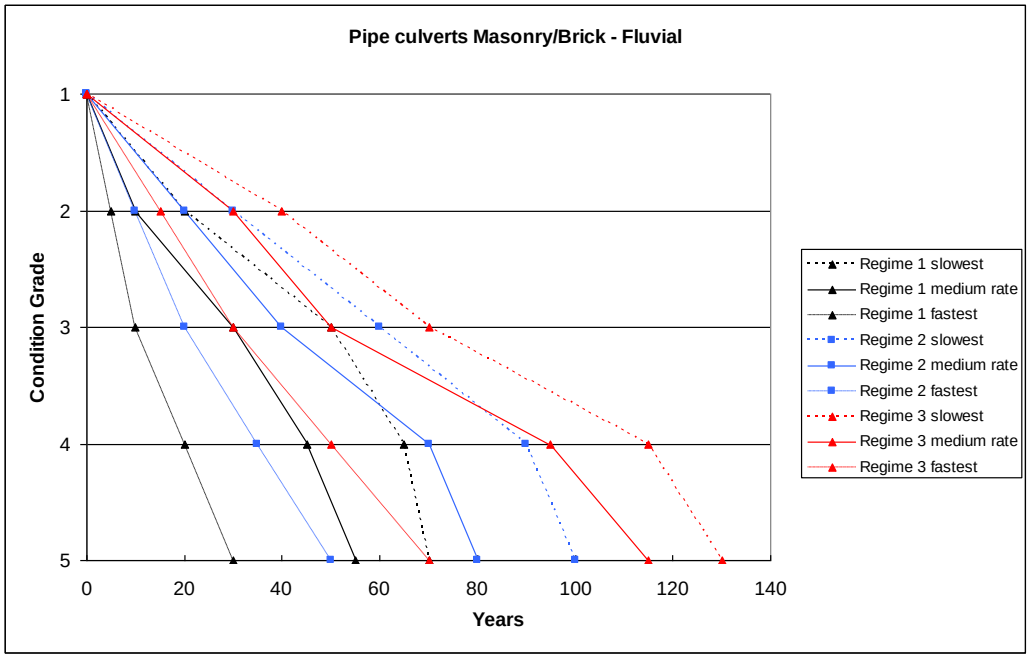

Figure 4.3 Deterioration curve for masonry/brick culverts, for fast, slow and medium deterioration rates

The figure shows three sets of curves: (a) deterioration with basic maintenance (Regime 1) (black curves), (b) deterioration with moderate maintenance (Regime 2) (blue curves) and (c) deterioration with high-level maintenance (Regime 3) (red curves). Each set comprises: medium estimate, fastest estimate (shortest life) and slowest estimate (longest life) (as above). For the purpose of clarity, the main analysis above (Section 4.3.3) considered only one curve from each set with three maintenance regimes. The WLC tool, however, contains three curves per set representing the three deterioration rate scenarios (see also Section 3.4.3).

It is to be noted that the user interface has been developed to allow the user to select the scenario applicable to the asset in question, i.e. whether slow, mid-range or fast deterioration applies.

4.4 The prototype WLC tool

4.4.1 Whole life cost analysis

A prototype WLC tool has been developed and customised for application to the specific purpose of operational flood defence asset management. The model is designed to be robust flexible and practical. As proof of concept, it is currently a stand-alone prototype tool, although it could be easily linked or included as part of wider developments of asset management systems.

Deterioration curves and rates for each of the assets under study are contained within the prototype tool, to guide when to maintain and replace the assets, as illustrated in the conceptual diagram of the WLC tool in Figure 4.4.

Table 4.16 lists user needs and how these are mapped to the functionality in the Halcrow WLC tool.

Table 4.16 Mapping of user needs to WLC tool functionality

User need	Comment	Matching functionality of Halcrow WLC tool
Availability to users	Is it readily accessibly, e.g. on work stations using readily available programs (e.g. MS Excel)	Tool is Excel based and has been provided to the Environment Agency
Straightforward data entry	Terminology and descriptions conform to Environment Agency practice	Tool is constructed to ensure conformity
Prompts and help fields	Explanations provided where user has to make a choice, e.g. with specifying expected rate of deterioration applicable (fast, medium, slow)	Tool is constructed to ensure conformity. User guidelines provided
Outputs are consistent with subsequent use for data/information (e.g. input into SAMPs)	The user may want to input the WLC profiles into SAMPs or similar	Tool outputs are tabulated (Excel file format) and include graphical data presentation

The WLC prototype tool has been set up to allow sensitivity analysis, to evaluate the sensitivity of the output to key parameter inputs.

An internal short guide has been prepared to describe the functionality, application and outputs of the prototype tool. Reference should be made to this document for information future applications for research.

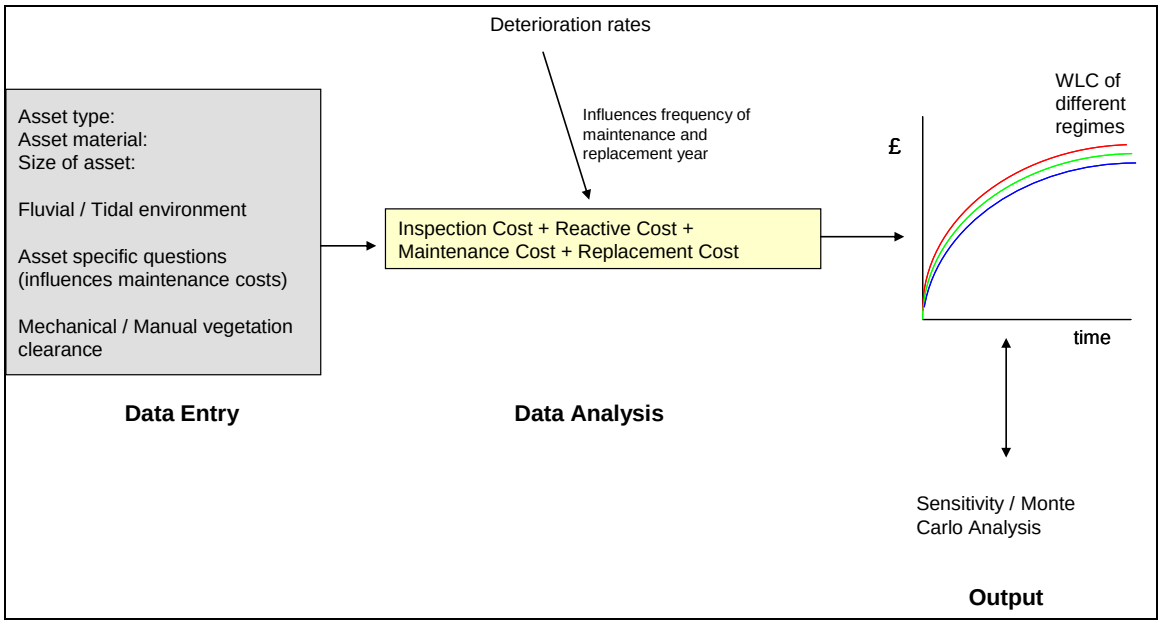

Figure 4.4 Conceptual diagram of the WLC prototype tool

4.4.2 Sensitivity analysis

Sensitivity analysis is a fundamental element in option appraisal analysis. It assesses the sensitivity of the output to changes in key input variables. There are four different scenarios of sensitivity analysis available in the WLC prototype tool. These are:

1. Percentage change around maintenance and replacement costs.
2. Change in years of transition points.
3. Change in percentage increase in maintenance costs.
4. Change in major repair/refurbishment cost (i.e. change in percentage of replacement costs).

The user can change the percentages for each of these scenarios and review the results of sensitivity analysis, in both graphical and tabular format.

4.5 WLC prototype tool – closing comments

This stage of the project has seen the development of a full set of maintenance cost profiles for all assets on the study list. These profiles form the basis of prototype for a WLC spreadsheet tool. The WLC prototype tool illustrates how asset managers and practitioners could assess the whole life costs under different levels of maintenance (as defined in the Environment Agency maintenance standards and the aligned maintenance regimes developed as part of this study.

5 Conclusions

A series of deterioration models and associated practical guidance (see separate SR1 report) have been developed to provide improved estimates of deterioration, residual life and illustrate impacts of life time costs.

The outputs support asset managers and operational staff within the Environment Agency in undertaking deterioration analysis, help to inform future management and maintenance and support planned work activities to optimise outcomes delivered through the maintenance programme.

A prototype Whole Life Costing Model has also been developed to illustrate how asset deterioration could be considered in a WLC context as part of wider improvements to FCRM asset management systems.

The prototype tool displays asset condition profiles and whole life cost profiles for the selected asset type for various scenarios representing various combinations of:

- location (either fluvial or coastal/estuarine);
- maintenance regime: (1) basic, (2) medium or (3) high levels of maintenance activity;
- likely deterioration rate (as influenced by environment (sheltered to exposed) and quality of materials/construction (poor to good)).

The prototype tool shows how whole life costs could be estimated for current Environment Agency maintenance practice (which for a number of assets is typically basic level activity potentially due to funding issues) and the impact of alternatives of increased maintenance activity to be assessed (in terms of cost and asset condition profile).

The prototype tool is adaptable to further development outside the scope of this project including incorporation of benefit analysis and optimisation components for instance as part of a wider approach to managing FCRM assets and data systems.

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Appendix A: Deterioration models – asset by asset

Issued separately

Appendix B: Maintenance standards developed during the project

Issued separately

Appendix C: Asset replacement costs

The table below provides the replacement costs for all the assets covered in this project. Cost data have been updated from the actual construction year to 2010 prices using the Office for National Statistics' Consumer Price Indices (CPI, http://www.statistics.gov.uk/statbase/Product.asp?vlnk=868).

Costs shown do not make any provision for:

- claims – e.g. unexpected ground conditions, etc.
- disruption costs.

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
Vertical walls (per km)	Concrete – wall raising	775,000	2,390,000		Access constraints Wall height Weather	Environment Agency Flood Risk Management Estimating Guide – Update 2010	No distinction made between construction types
	Concrete – retaining wall	576,000	13,830,000	60 (coastal)			
	Brick and masonry – wall raising	775,000	2,390,000	100 (fluvial)			
	Brick and masonry – retaining wall	576,000	13,831,000				
	Timber walls (fluvial)	1,494,000	2,419,000		Quality of materials used	HR Wallingford Whole Life Costs and Project Procurement report, 2003	Rates updated using CPI rates
	Timber walls (coastal)	2,242,000	3,629,000				
	Gabion wall	60,600	605,700	10	Economies of scale	Scottish Natural Heritage Dune Management Guide 2000	High cost is assumed to be ten times the low cost Rates updated using CPI rates Alternative rate of £165 to £495 per m^3

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
Sheet piled structures (per km)	Anchored steel and cantilever steel – urban	1,309,000	15,566,000	60 (coastal)	Mobilisation costs Type of piling Section size of piles Access constraints Location (urban or rural) Weather Economies of scale	Environment Agency Flood Risk Management Estimating Guide – Update 2010	No distinction made between construction types
	Anchored steel and cantilever steel – rural	370,000	2,811,000	100 (fluvial)			
Demountable defences (per km)	Metal	1,843,000	2,476,000		Access Mobilisation Stand-alone or mounted Height of defence Storage	Environment Agency Flood Risk Management Estimating Guide – Update 2010	Rates based upon sheet piling rural and urban, >100 m
	Wood	921,500	1,238,000				Rates based upon 50% of metal demountable defences costs

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
Earth dykes or embankments (per km)	Without slope/toe protection (varying core material, e.g. clay, shale)	342,000	4,284,000	100	Transport distance for fill material Type and source of material Access (haul length) Weather (winter working will likely have increased costs) Economies of scale Size – cubic metres	Environment Agency Flood Risk Management Estimating Guide – Update 2010	Assumes average volume of 18 m^3/m, using the widest range of material costs
	With slope/toe protection or revetment	376,200	4,712,000	100			Estimated: Added 10% to varying core material
Sloping walls with slope protection (per km)	Turf	342,000	684,000		Source, type and quality of materials used Access constraints Weather Availability of equipment	Environment Agency Flood Risk Management Estimating Guide – Update 2010	Based upon varying core material embankments for low, then doubled this cost for high
	Permeable revetments	1,817,000	4,542,000	60 (coastal) 100 (fluvial)		Environment Agency Flood Risk Management Estimating Guide – 2007	25% less than impermeable revetments
	Impermeable revetments	825,700	3,476,000	40 (coastal) 100 (fluvial)		Environment Agency Flood Risk Management Estimating Guide – 2007	15 projects (between 15.5 and 2830 m long structures) NB: 20%ile and 80%ile values used for low/high rates Updated using CPI rates

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
Culverts – pipe, box, arch (per km)	Concrete/masonry/ brick	900,000	25,000,000	100	Access constraints Weather Quality of materials used Size – longer lengths with smaller diameters will have lower cost rate	Environment Agency Flood Risk Management Estimating Guide – Update 2010	Rates are for rectangular or square sections Minimum rate for any culvert of any size is approximately £53,000 (Environment Agency Flood Risk Management Guide 2010) Rates cover 10 to 300 m lengths and 0.5 to 12 m^2 cross-sections
	Steel	900,000	25,000,000	100			
	Plastic	720,000	20,000,000				Estimated: 20% less than steel culverts
	Ferrous/clay	720,000	20,000,000				
Beaches without beach control structures	Recharge with sand per m^3 (per km)	13 (686,100)	32 (5,367,000)	15	Source, type and quality of materials used Access constraints Weather Availability of equipment	Per m^3 costs: Environment Agency Flood Risk Management Estimating Guide – Update 2010 Per km costs: Low cost rate – Halcrow Arun to Adur Strategy 2007 High cost rate – Halcrow Folkestone to Cliff End Strategy 2008	Per m^3 costs: Based on rates from four projects (high: 28,000 m^3 and low 689,000 m^3)
	Shingle recharge (per m^3)	1	25			Low cost rate – Environment Agency Flood Risk Management	Low rate is the cost of 360,000 m^3 of shingle recycling (2

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
						Estimating Guide – Update 2010 High cost rate – Halcrow Folkestone to Cliff End Strategy 2008	km haul) Rates updated using CPI rates
Beach control structures	Timber groynes (per m of groyne)	540	1,280	10–25	Source, type and quality of materials used Access constraints Weather/exposed working conditions Availability of equipment	Low cost rate – Halcrow costs database 2009 High cost rate – Halcrow Arun to Adur Strategy 2007	Assumes a groyne length of approximately 100 m Rates updated using CPI rates
	Rock groynes (per 100 m of groyne)	129,600	267,200			High cost rate – Halcrow Arun to Adur Strategy 2007 Low cost rate – Halcrow costs database 2008	Rates updated using CPI rates
	Terminal rock groyne (per 100 m of groyne)	167,000	330,300			Low cost rate – Halcrow Costs Database 2008 High cost rate – Halcrow Aldeburgh Coast and Estuary Study	High cost rate includes £41,637 for prelims and supervision Rates updated using CPI rates
	Placement of rock (per m^3)	9	470	60		Environment Agency Flood Risk Management Estimating Guide – Update 2010	Rates are based upon nine projects (high: 2,180 m^3 and low: 257,000 m^3) Alternative rate of £33–52/tonne (Aldeburgh Coast and Estuary Study)
	Crib walls – fluvial (per km)	1,494,000	2,419,000				As for timber wall (fluvial)

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
	Crib walls – tidal (per km)	2,242,000	3,629,000				As for timber wall (coastal)
	Breastwork – fluvial (per km)	1,494,000	2,419,000				As for timber wall (fluvial)
	Breastwork – tidal (per km)	2,242,000	3,629,000				As for timber wall (coastal)
	Offshore breakwater per m^3 (per km)	230 (14,560,000)	470 (29,110,000)			Environment Agency Flood Risk Management Estimating Guide – Update 2010	High cost same as placement of rock (includes sea placement). Low cost is 50% of high
Dunes with or without holding structures	per km	21,000	48,000		Source, type and quality of materials used Access constraints Weather	Environment Agency Flood Risk Management Estimating Guide – 2007	Rates are based on four projects, range of regional schemes Rates updated using CPI rates
Saltmarshes, saltings and warths with or without holding structures	per m^3 (per km)	1.3 (68,600)	25 (536,700)			Cost from Horsey Island case study – beneficial reuse gave low costs of approx £1.30 per m^3 (Note: £5 per m^2 is a figure used in the Resilience Partnership Funding (as average cost of creating intertidal habitats))	High cost per m^3 assumed same as for shingle recharge. Costs per km assumed to be 10% of beach per km costs

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
Maintained channel (per km)	Earth (simple channel)	100,000	1,000,000	100	Access constraints Environmental concerns	Environment Agency Flood Risk Management Estimating Guide – 2007	High cost is assumed to be ten times the low cost Rates updated using CPI rates
	Concrete/masonry/ brick (engineered channels)	213,700	2,137,000	100			
Weirs	(per m)	8,300	26,600	100	Access constraints Weather Quality of materials used Type of weir (fixed, narrow fixed or moveable)	Environment Agency Flood Risk Management Estimating Guide – 2007	Three projects (between 20 and 49 m long structures) Rates updated using CPI rates
Outfalls	(per km)	1,709,000	17,990,000	60 (coastal)	Access constraints Weather conditions	Environment Agency Flood Risk Management Estimating Guide – 2007	Eight projects (between 4 and 21.5 m long structures) Rates updated using CPI rates
				100 (fluvial)			
Flap valves	(per unit)	370	3,400		Type of structure Location	Environment Agency Flood Risk Management Estimating Guide – 2007	Five projects Rates updated using CPI rates

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
Moveable gates manually operated	(per unit)	20,200	379,500		Type of structure Location	Environment Agency Flood Risk Management Estimating Guide – 2007	Ten projects NB: 20%ile and 80%ile values used for low/high Rates updated using CPI rates
Moveable gates electrically operated	(per unit)	27,200	509,200		Type of structure Location	Environment Agency Flood Risk Management Estimating Guide – 2007	Two projects (provide low value). High value estimated as pro rata increase on manual high (as electrical low is on manual low) Rates updated using CPI rates
Debris screens	(per unit)	26,500	262,000		Type of structure Location	Environment Agency Flood Risk Management Estimating Guide – 2007	16 projects NB: 20%ile and 80%ile values used for low/high Rates updated using CPI rates

Asset class	Structure description	Indicative cost ranges £ per unit indicated		Estimated 'do nothing' life (years)	Factors influencing cost rate	Source	Comments
		Low	High				
Flood gates and barriers – metal and wood	(per unit)	47,500	5,783,000		Type of structure Location	Environment Agency Flood Risk Management Estimating Guide – 2007	Ten projects (include timber (2) and steel (1) plus others with unspecified material) Rates updated using CPI rates

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Horizon House
Deanery Road
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Tel: 03708 506 506

Email: enquiries@environment-agency.gov.uk

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