Department for Environment Food & Rural Affairs

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delivering benefits through evidence

Impact of climate change on asset deterioration

Appendix C – Quantification of vulnerability

Report - SC120005/R4

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Contents

1 Approaches

1.1 Introduction

An ultimate goal from this study is to help inform where future efforts, and potentially investment, may need to be targeted to address the impacts of climate change on asset deterioration. This project is developing some of the knowledge, information and approaches to support that. It is also seeking to develop that knowledge to be able to help practitioners gain a better understanding of how climate change may affect asset deterioration and how to consider that in both future assessments of requirements and potentially futureproofing designs at the local level.

This particular appendix presents the work on assessment of approaches to deliver on the above goals and some information on approaches that will be useful as this matter is further developed in the future. It provides some illustrative examples of how climate change factors can alter the requirements for maintaining or repairing assets, considering a range of different deterioration/damage mechanisms.

The information provided in this appendix is as follows:

- An overview of different assessment techniques.
- An appraisal of the potential availability and suitability of quantification methods for various asset types (with detailed information captured in Section 2).
- Illustrative examples of how to quantify the impacts of a change in climate upon particular aspects of asset deterioration (with worked examples presented in Section 3).
- Considerations for further development of methods to support a national level application.

Further discussion on the outcomes of this are contained within the main study report.

1.2 Assessment techniques

There exist a range of levels and associated techniques at which an assessment might be performed, with varying levels of complexity and data requirements, for example:

- Engineering judgement/assessment based upon asset-specific information (e.g. visual assessment).
- Broad assessment, using basic information regarding the asset (such as the mandatory geometric data fields in the Environment Agency's Creating Asset Management Capacity or CAMC programme).
- Good basic site-specific information and knowledge of form of structure, basic geometry and site conditions.
- Good information on the form and dimensions of a structure enabling robust assessment of performance characteristics.
- Very detailed information (e.g. site investigation) enabling sophisticated calculation.

At the simplest level, purely qualitative approaches exist and different approaches might be considered. Expert judgement, such as used in condition characterisation, forms an important element of risk assessment. However, it is rarely precise and is not quantitative. In some studies, qualitative data has been utilised to produce some 'rules' that offer the opportunity to assign certain risks to different structure types in different sets of circumstances, and this does have some merits for high level prioritising and screening for example.

The other end of the scale is to carry out a fully quantitative assessment of vulnerability. The techniques to assess the vulnerability of any asset to climate change impacts will be similar to those used to design and analyse those same assets without climate change; it is simply that some of the input variables will change over time. The question to be addressed, however, is how to obtain sufficient information to make that assessment meaningful without extensive additional data collection. The application of such methods therefore depends upon the quality and accuracy of the outputs required, which in turn will be determined by the intended use of those outputs.

There are then approaches that require a degree of quantification combined with more qualitative (and perhaps even subjective) information. These 'hybrid' approaches might be considered to provide a probabilistic assessment of vulnerability, but again with different levels of data requirements and associated differing levels of quantification.

A description and appraisal of the applicability of these approaches to addressing the questions posed for this study is presented in Table C1.1.

TECHNIQUE	APPLICATION/APPROACH	SUITABILITY FOR NATIONAL ASSESSMENT PURPOSES
Qualitative approaches		
1) Expert review of generic asset types.	Approach could be to have several experts conduct the same exercise to determine the level of consensus and variance on that. The outcome will though be no better than a High/Medium/Low analysis for a generic type of asset, with many caveats.	The application of purely qualitative techniques for generic asset types will have limitations for a national level impacts appraisal. For example, expert review of generic structure types could only be expanded nationally by counting the number of each asset type that exist, but that tells us very little about the level of impact at the national level. Such approaches may, however, have some potential for high level screening.
2) Expert review of generic asset types but taking into account key variables, for example physical setting. Almost certainly to have any applicability this must be made more location specific.	At the first level this could be extending the analysis to a combination of asset type and setting, for example. the same as above but considering a fluvial structure with different bed materials.	
3) The next potential level of assessment focuses on making maximum use of collected data without the need for additional data collection, and developing 'rules' for specific attributes. This is largely akin to the Highest-Level Methods in RASP etc.	The approach is to establish certain potential outcomes based upon certain attributes for different structure types, if appropriate setting rules. For example, if Attribute A = 'High' and Attribute B = 'Type X' and Attribute C = 'Yes', then outcome is OK/not OK or High/Medium/Low but with fewer caveats than a purely qualitative approach.	This could be applied as a first high level assessment at national level to differentiate between the relative levels of vulnerability of different assets, and perhaps for high level prioritisation. The absence of quantification would however constrain the extent to which the impacts from climate change could be determined.
Quantitative approaches		
1) At simplest level, basic geometric data and information on forcing conditions could be used to perform the most basic of calculations (e.g. seawall overtopping). These would use core information that should be collected for national asset databases.		This is very achievable at national/regional level but will be limited by the level of data population within existing asset databases, and the limitations of the data fields that exist within those.
2) The technique presented above uses information that is relatively basic and the approaches can be refined if some additional information were collected as part of a national database, for example ensuring that information on toe levels was obtained, leading to the accuracy being improved.		This approach is easily developed and applied, but is dependent on resources to collect the necessary information. A further refinement may also be in the geographic resolution of forcing parameters.
3) A third level would be more robust calculations which used more (albeit still basic) data such as that which existed in the old Sea Defence Survey and Coast Protection Survey of England. This will better describe the form of structure and thus the specific assessment tools/formulae, providing a much more accurate appraisal of vulnerability to climate change. Even at this level it can then have facility to link for example to the neural networks for overtopping. Likewise, the assets can be linked to the data from the regional coastal monitoring programmes in England (e.g. those data held at http://www.coastalmonitoring.org).		Can still be easily automated, but this would have the potential inconvenience that not all this data can presently be captured in CAMC. This is probably the most detailed level that any national/regional assessment would go to and perhaps too detailed for all but a small proportion of cases.

TECHNIQUE	APPLICATION/APPROACH	SUITABILITY FOR NATIONAL ASSESSMENT PURPOSES
Hybrid approaches		
1) Use of some quantitative information in conjunction with the more advanced qualitative 'rules', and, where it is not available, surrogates for that.	This is largely akin to the HLM+ methods in RASP and as used for NaFRA. In these, although the geometric properties of structures are not well defined, certain key elements such as crest level are incorporated together with some geographically broad definition of forcing parameters (river flows, water levels). Where crest levels are not available this is inferred from the reported SoP and the broad water levels. These are used in combination with some very broad 'look-up' values for factors such as overtopping rates based upon the combination of some of these parameters.	Again some of the limitations of data availability remain but approaches to deal with that can be developed. The accuracy of outputs remains limited and would still be caveated at the general level but this might offer a very good and reliable second tier assessment, for example offering some quantification and also further screening with a degree of relative vulnerability levels between different assets of similar type.
2) Develop a wide range of conditions and potential impacts for each asset as look-up tables/graphs/charts.	These could be coded as look-up tables/graphs which could then be applied as factors based upon the structure type and other attributes used in NaFRA and NCERM. For example, consider a wide variety of freeboards, water depths, wave heights and structure types and produce graphs of overtopping, with a corresponding set of graphs for a range of different sea level rise increases.	A further possibility for a hybrid approach. Indeed, this is how wave conditions/overtopping have historically been accounted for within LTIS, which was relatively crude but can be improved upon for those applications.
3) Within this group of techniques, another approach would be to find a way to adjust deterioration curves.	The difficulty here is, in the case of deterioration curves, the accumulative approach in which they consider processes and in the case of fragility curves, the transparency of how they have been developed. So, to do so meaningfully and with confidence on the accuracy would require unpicking these to isolate the variables that can be influenced by climate change and reconfigure with ability to modify accordingly.	Adjustment of fragility curves would make those readily useable within NaFRA for example (but not NCERM). But whether these are sufficiently defined to (a) enable the refinements described here to be made and meaningful, and (b) already extensive enough to cover the full range of asset types adequately is debatable.

Table C1.1 Description and appraisal of the applicability of different qualitative, quantitative and hybrid approaches

1.3 Methods for quantification

1.3.1 Qualitative assessment and screening

The qualitative assessments provide an asset-by-asset type appraisal of the deterioration processes and how climate change may affect those. From that, and in that context, the assets most likely to be vulnerable to climate change and the main factors driving that have been established, with an initial categorisation of vulnerability defined as ‘High’, ‘Moderate’, ‘Low’ or ‘Negligible’ (see Appendix B).

This information has been used to screen those assets for which advanced (i.e. quantifiable) methods could be developed for assessment of potential impacts, and which processes to focus most attention upon (i.e. those categorised as either ‘Moderate’ or ‘High’).

1.3.2 General appraisal of quantification methods

At the highest level, some initial assessments have been made of the potential methods that could be applied to carry out more advanced quantitative assessments.

Section 2 of this appendix presents an initial appraisal of the methods and techniques that might be applied to provide a more advanced quantitative assessment for each asset type. Likewise, where practical methods are unlikely to exist, these limitations are also identified.

The suitability of these approaches also depends upon data availability and precision of outputs required, but they do provide a starting point for considering the development of quantifiable methods.

1.3.3 Common methods

Arising from this, the possibility of developing some methods that might be applied across a range of different asset types in certain environments is also apparent. Examples of this include the effects of beach scour on several different types of coastal assets; similarly channel scour on many fluvial assets. Through appreciating this, there will be aspects of deterioration that can be considered collectively when considering suitability of methods to quantify impacts.

To further investigate this possibility, it is necessary to understand at a broad level what the key and common deterioration processes are. To inform that, each of the individual qualitative assessments have been reviewed to capture the deterioration processes most significantly affected by climate change that have been identified for each. A summary of that is presented in Tables C1.2 to C1.4 for the assets where vulnerability has been determined to be Moderate or High (Appendix B).

This is not exhaustive, and the deterioration processes most affected will alter from asset to asset rather than remain constant for all within any particular asset type. Nonetheless, this provides some indication of key processes where attention may be focused in terms of developing quantifiable methods to be applied for national level appraisal.

FLUVIAL	Overflow damage	Toe scour/ undercutting	Cover layer displacement	Abrasion/ corrosion	Erosion/ volatility	Geotechnical instability	Wear and tear	Uplift/ displacement	Impact damage
CHANNEL BANK (all)		X	X						
BRIDGE		X						(x)	X
EMBANKMENT (turfed)	X	(x)			X	(x)			
EMBANKMENT (protected)	X	X	X			X			
RAISED RIVER WALL				(x)				X	
CONTROL GATE (mitre gate)							X	X	(x)
WEIR		X							
SPILLWAY				(x)		X			
JETTY		X							
PUMP HOUSE							X		

Table C1.2 Primary deterioration processes – fluvial assets

COASTAL		Overtopping damage	Toe scour/ undercutting	Cover layer displacement	Abrasion/ corrosion	Erosion/ volatility	Seepage	Wear and tear (use/forces)	Uplift/ displacement	Joints/loss of fill
EMBANKMENT		X	X	X						
SEAWALL (vertical)			X		X					(x)
SEAWALL (revetment)		(x)	X	X						
FLOOD GATE					(x)			X	X	
DEMOUNTABLE								X		
BEACH						X				
DUNE						X				
BARRIER BEACH		X				X	X			
CLIFF (unprotected)						X				
OUTFALL			X		(x)					
GROYNE (timber)					X	(x)				
SLIPWAY (concrete)			(x)							X
SLIPWAY (timber)					X				X	
STEPS (concrete)			X		(x)					(x)
STEPS (timber)					X				X	
RAMP			X		(x)					(x)

Table C1.3 Primary deterioration processes – coastal assets

ESTUARY	Overtopping damage	Bed Scour/ undercutting	Cover layer displacement	Abrasion/ corrosion	Erosion damage	Wear and tear	Uplift/ displacement	Impact damage
BRIDGE		X					(x)	X
EMBANKMENT (protected)	X	X	X					
EMBANKMENT (turfed)	X	(x)			X			
VERTICAL WALL	X	X		(x)			X	
SALTMARSH					X			
CONTROL GATE (mitre gate)						X	X	(x)
WEIR		X						
JETTY		X					(x)	X
BEACON		X						X
PUMP HOUSE						X		

Table C1.4 Primary deterioration processes – estuary assets

The methods available to quantify these processes, and thus the effect on deterioration resulting from climate change, exist for some but not for all. It is relatively easy to utilise existing well-established formulae to assess the likely increase in level of maintenance and repair requirements for increased overtopping/overflow damage, for higher levels of damage/instability to protective cover layers, or for greater scour around the toe of structures. It is, however, more difficult to calculate the change in requirements to deal, for example, with impact damage or wear and tear (e.g. does a 30% increase in river flows directly correspond to a 30% increase in operation, maintenance or repair activity?) There are also processes for which the change in requirement might be calculable, but only at an asset-specific level with design-level detailed data; for example, the consequences of changes in forces on flood gates, or potential for seepage/geotechnical instability.

1.3.4 Illustrative examples

To illustrate how some existing formulae might be utilised to quantify the impacts of a change in climate upon particular aspects of asset deterioration, a series of examples are presented in Section 3 of this appendix.

In each of these illustrations a different potential issue has been examined (e.g. scour, displacement, overtopping), which is described therein together with the type of assets this might be applicable to. A worked example is then presented using a basic equation to show how the input parameters would change as a consequence of climate change and thus how the results will alter. This is made clear in the illustrations by showing the parameter and changed value coloured red. Using these worked examples it is easy for the reader to both follow the worked example and see why climate change will affect the outcome, and indeed understand how to apply a similar assessment to their own situations.

It must be noted that the equations are not necessarily the definitive state-of-the-art design formulae, but are well established and easy to follow, so are selected here simply to demonstrate the effects of climate change within such calculations and enable the reader to appreciate exactly how climate change could alter the requirements for an asset.

The asset properties and values for hydrodynamic conditions used in these illustrations are not unrealistic for parts of the UK, but it is stressed that actual conditions across the UK do vary considerably from these. The examples presented in Section 3 have been chosen to best illustrate how changes in hydraulic parameters as a consequence of climate change could alter the magnitude of any asset deterioration mechanism.

It is advised that anyone considering using these methods to assess their own assets must ascertain for themselves whether these are indeed the most relevant approach for their particular asset, considering also the bounds of applicability of those formulae.

In applying these or similar calculations, it is important to also be cognisant of how certain input parameters might be influenced by other physical conditions.

- At the coast, for example, larger waves are often depth limited so it is necessary to understand whether the baseline condition has waves which already exceed that limit. If so, then any increase in sea level will also see a change in wave height proportional to the water depth irrespective of any change in incident wave climate. Likewise, if there is no increase in water level, a change in offshore wave height may in fact result in little difference at the asset as the higher waves remain constrained, albeit their breaking characteristics may alter.

- In a fluvial situation, it is important to recognise that an increase in flow will not simply alter the flow velocity but also the cross-sectional area of flow, i.e. $Q = V \times A$; therefore, a 30% change in flow volume does not generally produce a corresponding 30% increase in flow speed. In simple terms, it might be estimated that the same change occurs in both, that is, increase in velocity and increase in area are both the square root of increase in flow. But that is a big assumption and can be altered considerably by the shape of the river channel, the depth of flow and whether out-of-bank flow results or not.

In summary, the examples presented here should be considered to be no more than illustrations to help improve understanding of how climate change effects might be taken into account in terms of quantifying asset deterioration, and provide the basic principles for others to adopt when seeking to undertake such analysis.

1.4 Further development of methods

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

Best methods are generally those that can be instantly and/or easily applied without recourse to significant data collection exercises. But at the same time assessment does not want to be 'dumbed down' to the lowest level when a more informative assessment is actually possible in many cases. Equally, methods that are 'data hungry' and require the same high level of information everywhere are not always appropriate if risks can already be determined to be relatively low.

The approaches that might be applied are quite varied and appropriateness will largely depend upon the level of risks that are a consequence of a change in asset deterioration and the degree of accuracy desired in the outputs. Not all techniques are appropriate for all assets, and where the more advanced approaches are applied more data is required so targeting that need to be cost effective is also important.

Due to the limitations on the data that is likely to be available, any quantification of deterioration is likely to require some form of hybrid approach; for example, generating rule bases to calculate potential changes in deterioration for individual assets in a way that can also be codified to allow application at a national level.

An extension of that is to create look-up tables for which values for a series of different combinations across a range of typical conditions can be calculated, against which individual assets can be compared and the results of the change in condition are identifiable from that same table. Look-up tables could take two forms: first, the adoption of typical values based upon individual asset characteristics without recalculation for each asset, which is useful where some data is incomplete; and, second, comparing to thresholds for damage or instability for different material/element types (such as protection systems) to establish whether the increase triggers the requirement for further action or not.

The examples below in Tables C1.5 to C1.7 indicate how these might be constructed.

Depending upon how far the application is ultimately taken, a tiered methodology making use of available/obtainable information appropriate to a level of analysis commensurate with the wider risks is likely to be most practical. This means that a range of methods can be available and applied to obtain an output regarding impacts, each just being a more or less sophisticated technique that can be applied to an asset type utilising different levels of data.

The benefit of using a tiered approach to risk assessment of assets is widely recognised as particularly appropriate for situations where the quality and extent of data available for the assessment is not consistent within the set of structures being considered. The variation in data quality and types suggest a range of methods that have a complexity that is both commensurate with the data quality and also the use of the results. Importantly, any approach should reflect the level of uncertainty in the input data and methodology in the level of detail provided in the output.

OVERTOPPING DAMAGE		***Freeboard (m)***					
		Low	---------------------------------→				***High***
Water depth (m)	***Deep***						
	↑						
	↑						
	↑						
	↑						
	Shallow						

Table C1.5 Look-up table: Example 1

SCOUR DEPTH (Bed Material X)		***Channel cross-sectional area (m²)***					
		Small	---------------------------------→				***Large***
River flow (m³)	***High***						
	↑						
	↑						
	↑						
	↑						
	Low						

Table C1.6 Look-up table: Example 2

RIVER BANK PROTECTION		***???***		
		Small	---------------------------------→	***Large***
Flow velocity (m/s)	***Fast***	***Heavy permeable***	***Impermeable***	***Impermeable***
	↑	***Medium permeable***	***Heavy permeable***	***Impermeable***
	↑	***Light permeable***	***Medium permeable***	***Heavy permeable***
	↑	***Turf (reinforced)***	***Light permeable***	***Medium permeable***
	↑	***Turf***	***Turf (reinforced)***	***Light permeable***
	Slow	***Turf***	***Turf***	***Turf (reinforced)***

Table C1.7 Look-up table: Example 3

Axes on such tables might include:

- water depth (coast)
- flow volume or speed (river)
- cross-sectional area or water depth (river channel)
- freeboard (coast or river)
- foreshore type/mobility/beach level change (coast)
- channel bed type/mobility/level (river)
- capacity (flow structures)
- material/system type (erosion/stability coverings)

2 General appraisal of quantification methods

C2.1: Channel

C2.2: Channel crossing

C2.3a: Defence – Embankment

C2.3b: Defence – Wall

C2.3c: Defence – Other

C2.4: Land

C2.5: Structure

C2.6: Beach structures

C2.7: Instruments

C2.8: Aids to navigation

C2.9: Buildings

C2.10: Major civils

2.1 Channel

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
1.1	OPEN CHANNEL (Fluvial)	-	**No**	
1.2	SIMPLE CULVERT	-	**No**	
1.3	COMPLEX CULVERT	-	**No**	

2.2 Channel crossing

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
2.1	BRIDGE	(Fluvial/Estuary)	**YES**	There are no obvious methods for assessing the deterioration of bridges at a generic level; the impacts are likely to be bridge/design specific. Calculation methods for estimating scour around base of the bridge piers might be adopted. However, a generic/high level assessment is difficult as the determining factors on vulnerability will be entirely case specific. It is also probable that the information on the structures to support such calculations is not recorded. However, given two key potential impacts are scour around the bridge piers and potential for the deck to become impacted, methods to look at changes in river bed levels due to higher flow velocities and increases in water levels might be considered.
2.2	UTILITY SERVICES	-	**No**	

2.3 Defence

2.3.1 Embankment

<table>
<tr><th colspan="3" rowspan="2">Asset</th><th colspan="2">Advanced methods warranted?</th></tr>
<tr><th>Yes/ No</th><th>Considerations for advanced methods</th></tr>
<tr><td rowspan="6">3.1</td><td rowspan="6">EMBANKMENT</td><td>With Revetment Type Seawall (Coastal)</td><td>YES</td><td>The standard design equations and thresholds for damage can be readily applied to determine the change in requirements with respect to cover layer, crest and rear face protection for these structures with adjustment to waves and water levels. These will need some basic definition of structure geometry, beach level and design conditions. If these are not available, then hybrid (semi-quantitative) methods utilising best available data may be possible to make some assessments of the relative changes in vulnerability as a result of these factors.
Assessment of changes to internal instabilities will be more difficult to undertake unless detail is known on some of the geotechnical parameters for those existing assets (which is unlikely). Again, however, it might be possible to explore whether generic assessments could help to establish whether the climate change factors being considered are likely to be of a magnitude to be of concern – but whether this is justified or going to be of value to a national level assessment would need to be determined.
It is also worth considering the date of construction/refurbishment of these assets; if carried out in the past two decades then it is possible that the impacts of climate change on them have already been taken into account by the present design.</td></tr>
<tr><td>With Revetment (Estuary)</td><td>YES</td><td>Similar to coastal embankments.</td></tr>
<tr><td>Unprotected – Turfed only (Estuary)</td><td>YES</td><td>Similar to fluvial embankments but with the addition of wave impacts on erosion and overtopping.</td></tr>
<tr><td>Unprotected – Turfed only (Fluvial)</td><td>YES</td><td>Standard design rules can be used to assess crest level of embankments against estimated climate change water level increases. These could be used to determine the potential for damage thresholds due to overflow to be exceeded.
Similarly, flow velocity changes due to climate change can be determined to establish whether typical thresholds for turfed embankment erosion would be exceeded.</td></tr>
<tr><td>Protected by Permeable Revetment (Fluvial)</td><td>YES</td><td rowspan="2">Standard design rules can be used to assess crest level of embankment against estimated climate change water level increases. This could be used to determine the potential for damage thresholds due to overflow to be exceeded.
Similarly, flow velocity changes due to climate change can be determined to establish whether typical thresholds for the erosion of the chosen type of revetment would be exceeded.</td></tr>
<tr><td>Protected by Impermeable Revetment (Fluvial)</td><td>YES</td></tr>
</table>

2.3.2 Wall

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
3.2	WALL	Vertical Seawall (Coastal)	**YES**	Quantitative methods could be used to assess overtopping. Standard design rules could also be used to assess the integrity of the wall design, but the wide variability in forms of construction make that virtually impossible without detailed individual inspection – there are too many unknowns. Hybrid methods might concentrate instead on beach types and levels (to consider potential exposure and volatility). It should be possible to develop different quantitative rules/assumptions related to different generic wall forms.
		Revetment Type (Coastal)	**YES**	The standard design equations and thresholds for damage can be readily applied to determine the change in requirements for these structures with respect to the stability of the revetment cover layer, with adjustment to waves and water levels. These will need some basic definition of structure geometry, beach level and design conditions. If these are not available, then hybrid (semi-quantitative) methods utilising best available data may be possible to make some assessments of the relative changes in vulnerability as a result of these factors. It is also worth considering the date of construction/refurbishment of these assets; if carried out in the past two decades then it is possible that the impacts of climate change on them have already been taken into account by the present design.
		Vertical Wall (Estuary)	**YES**	Similar to vertical wall at the coast.
		Raised River Wall (Fluvial)	**YES**	Implications for walls above the channel side are primarily a consequence of greater exposure due to high water levels as a consequence of river flows. Standard design rules could be used to assess the integrity of the wall design, but the wide variability in forms of construction would require detailed individual inspection and asset-specific details, so is not viable. Generic methods might concentrate instead on changes in water levels and frequency of exposure of the walls, with some cross referencing to generic wall type.

2.3.3 Others

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
3.3	FLOOD GATE	(Fluvial/ Estuary)	**No**	
		(Coastal)	**?**	Quantitative methods would involve using standard design rules to reassess a flood gate design against anticipated climate change increases, notably higher wave forces on the gate. This would however require individual design details. A more generic hybrid approach might be to assess the location and thus potential for exposure to direct wave forces of such gates and thus likelihood of them becoming more vulnerable.
3.4	DEMOUNTABLE	(Fluvial/ Estuary)	**No**	
		(Coastal)	**?**	Any assessment of the deterioration of a demountable defence will be individual asset-specific. The main consideration moving these from 'Low' to 'Moderate' at the coast is the increase in exposure to waves. Although a publicly available specification has been prepared for temporary and demountable flood protection products by the British Standards Institute with support from the Environment Agency, the design of each can differ considerably. At best, the approach that might be adopted would be to assess the location and thus potential for exposure to direct wave forces of such gates and thus likelihood of them becoming more vulnerable.
3.5	BRIDGE ABUTMENT	-	**No**	
3.6	HIGH GROUND	Natural/ Unlined (Fluvial)	**No**	
		Lined – Permeable (Fluvial)	**YES**	Quantitative methods would involve utilising standard design rules with the flow velocity changes due to climate change determined to establish whether typical thresholds for turfed bank erosion or stability for the type of revetment would be exceeded. Methods could also consider how changes in channel geometry in terms of bed levels and bank would affect scour (e.g. at the base of any revetment) and bank stability. Hybrid methods might for example concentrate on river bed types and levels (to consider potential for undermining). It might be possible to develop different quantitative rules/assumptions related to different channel forms.
		Lined – Impermeable (Fluvial)	**YES**	
3.7	QUAY	-	**No**	
3.8	BEACH	(Coastal)	**YES**	There are various numerical and empirical models for analysing beach profile response – the cross-shore models include X-Beach and Powell. Reference and commentary on such models can be found in the Environment Agency's 'Guidance for beach Modelling based on performance analysis of existing schemes. Important to those models is sediment size (which may not be in AIMS), but monitoring data on beach types and profile information (where available) would be a key source for any analysis. Numerical modelling would need to be site specific, so would not be advocated, but a range of other methods could support hybrid and quantitative approaches.
3.9	DUNE	(Coastal)	**?**	Although some numerical methods do exist to assess dune erosion (e.g. Vellinga), this will deal only with the dune face. Behind that, each dune system is unique and methods to assess any changes in vulnerability of a dune system are more subjective and need to be considered on a site-specific basis. There is no doubt, however, that rule-based methodologies could be developed to undertake a more advanced assessment. There are empirical assessment methods – mathematical relationships between key parameters such as dune profile, storm water levels and storm waves – that can be used to estimate dune erosion during storm events and/or timing of likely dune failure which could lead to flooding of the hinterland. These are generally developed through desk-top analysis using aerial photography, mapping and digital terrain data such as LiDAR. For example, Williams et al (2001) describes in 'Integrated Coastal Dune Management' how dune vulnerability can be assessed across a variety of dune sites using a checklist method, defining dune vulnerability as a reduced ability to adapt to change.

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
3.10	BARRIER BEACH	(Coastal)	**YES**	There are various numerical and empirical models for analysing beach profile response – the cross-shore models include Powell etc. and Bradbury work on barrier beach overwash, stability etc. Most recently a new model XBeach-G has been developed. Important to those is sediment size and grading (which may not be in AIMS). Barrier beach geometry is also going to be an important consideration – but other than crest elevation that is probably not in AIMS either. Other datasets such as from ongoing monitoring programmes can potentially provide some of these details. Numerical modelling would need to be site specific so would not be advocated, but a range of other methods could support hybrid and quantitative approaches.
3.11	PROMENADE	-	**No**	
3.12	CLIFF	Unprotected/ Natural (Coastal)	**?**	Rule-based methodologies exist for considering the effects of climate change on different cliff types (ref: SCOPAC work c.2000), which could be readily adopted. These methods would require datasets which are beyond those in CAMC, but nonetheless do exist. Empirical methods for estimating the increase in erosion rates as a consequence of sea level rise also exist, although those prediction methods are relatively crude. Baseline rates of change can be obtained from the Futurecoast and SMP datasets. Numerical models to predict cliff erosion can also be applied but these are very data hungry and require site-specific data that is unlikely to be widely available. Geology is a key/primary component but this is not captured in CAMC. Past rates of erosion are also an important consideration for any quantifiable analysis.
		Stabilised Slope	**No**	

2.4 Land

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
4.1	SALTMARSH	(Estuary)	**YES**	To look quantitatively at vulnerability to drowning, use spatial analysis (plan form and topography) and water levels to look at changes in inundation frequency. To look at erosion and accretion would require information on sediment concentrations and numerical modelling of flows, sedimentation rates etc. In both cases, such analysis would be very site specific rather than generic and data will not be immediately available. There is potential for hybrid methods (generic); for example, simple calculations on thresholds of motion to establish if the magnitude of changes being considered by this study would be likely to make a difference or not in terms of erosion.
4.2	MUDFLAT	-	**No**	
4.3	WASHLAND	-	**No**	

2.5 Structures

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
5.1	SCREEN	-	**No**	
5.2	IN CHANNEL STOPLOGS	-	**No**	
5.3	CONTROL GATE	Mitre Gate (Fluvial)	**?**	Quantitative methods could involve using standard design rules to reassess the design of the gate, lifting gear, support structure and gate orifice against anticipated climate change increases for individual gates or sets of gates. However, these will be individual gate specific and required design details – which are unlikely to be directly accessible and require a level of input beyond that which might be appropriate for a national level appraisal. Methods would therefore need to be more generic, and hybrid approaches that might be considered would instead need to focus upon changes in the number of operations and, related to that, the likelihood that the frequency of major refurbishments increases.
		Radial Gate	**No**	
		Rising Sector Gate	**No**	
		Guillotine Gate	**No**	
		Penstock	**No**	
		Generic (Estuary)	**?**	The primary aspects of deterioration identified are increased wear and tear resulting from more frequent operation and changes in loading. There are no immediately identifiable methods to assess the deterioration of components from wear and tear, but hybrid methods might consider the changes in extreme water levels and thus changes to the frequency of operation to estimate increased requirements in maintenance and replacement.
5.4	OUTFALL	-	**No**	
		(Coastal)	**?**	A quantifiable approach is not really viable – methods and data will not readily support this for national level appraisal. Increased maintenance commitment would be asset specific and dependent on a number of variables. The only factors that could be considered in terms of relative levels of maintenance would be the setting (i.e. is the beach sand or shingle) and thus the relative degree of exposure and vulnerability.
5.5	WEIR	(Fluvial)	**YES**	Quantitative methods would involve utilising standard design rules to reassess the flow capacity of weir and channel crest levels against anticipated climate change flow increases. Likewise, assessment can be made of the effect of increased debris on the operability of a weir. However, these would require asset-specific details; there are limitations to the extent to which methods can be applied generically with limited geometric and flow data.
		(Estuary)	**?**	
5.6	SPILLWAY	(Fluvial)	**?**	Key mechanisms include degradation of materials and displacement of elements, both of which would be difficult to assess generically; individual asset-specific assessments would be required.
5.7	STILLING BASIN	-	**No**	
5.8	DRAW-OFF TOWER	-	**No**	
5.9	FISH PASS	-	**No**	
5.10	HYDROBRAKE	-	**No**	
5.11	INSPECTION CHAMBER	-	**No**	
5.12	JETTY	(Estuary)	**?**	Methods for calculating uplift forces, and to estimate scour around piles, do exist and can be adopted. Quantitative assessment could also use standard pile design calculations to consider changes in water level, flow velocity and bed level, but would need data on pile size and depth of penetration into the bed. However, a generic/high level assessment is difficult as the determining factors on vulnerability will be entirely case specific. It is also probable that the information on the structures to support such calculations is not recorded.
		(Fluvial)	**?**	

2.6 Beach structures

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
6.1	GROYNE	Timber (Coastal)	**YES**	Quantitative methods would be the application of standard design rules (e.g. from Eurocodes). But assessing the vulnerability of existing assets without detailed individual inspection is not viable – there are too many unknowns (e.g. driven pile lengths). Hybrid methods might concentrate instead on beach types and levels (to consider potential exposure and volatility, and also to consider susceptibility to abrasion).
		Rock	**No**	
6.2	BREAKWATER	-	**No**	
6.3	SLIPWAY	Concrete (Coastal)	**?**	Design methods include ensuring cover to steel is adequate and that joints and seals are either maintenance free, or there is an allowance for maintenance in the operational planning. This is therefore specific to each structure and a quantifiable approach to assess the deterioration of these materials and elements at a higher national level is not really viable as details will be dependent upon a number of variables. The only factors that could be considered in terms of relative levels of maintenance would be the setting (i.e. is the beach sand or shingle). The main deterioration mechanism is undermining and collapse as a consequence of beach levels falling. Hybrid methods might therefore be undertaken as part of a broader assessment of beach variability as a consequence of climate change, and thus the potential vulnerability of individual assets to such variability depending upon their location.
		Timber (Coastal)	**?**	Quantitative methods would be the application of standard design rules (see Eurocodes). But assessing the vulnerability of existing assets without detailed individual inspection is not viable – there are too many unknowns (e.g. driven pile lengths). Hybrid methods might concentrate instead on beach types and levels (to consider potential exposure and volatility, and also to consider susceptibility to abrasion).
6.4	STEPS	(Coastal)	**?**	See Slipway – Concrete
6.5	RAMP	(Coastal)	**?**	See Slipway – Concrete

2.7 Instruments

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
7.1	INSTRUMENTS – ACTIVE MONITORING	-	**No**	
7.2	INSTRUMENTS – PASSIVE MONITORING	-	**No**	

2.8 Aids to navigation

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
8.1	BEACON	(Coastal/Fluvial)	**No**	
		(Estuary)	**?**	Methods for calculating uplift forces, and to estimate scour around piles, do exist and could be considered. However, although quantitative assessment could use standard pile design calculations to consider changes in wave loading and for bed level, which would need data on pile size and depth of penetration into the bed (not expected to be available), there is no way to predict the morphological response of the estuary at the location of these assets without numerical modelling on an estuary-specific basis.
8.2	BUOY	-	**No**	
8.3	SIGNAL	-	**No**	
8.4	SIGNAGE	-	**No**	
8.5	DOLPHIN	-	**No**	

2.9 Buildings

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
9.1	PUMP HOUSE	(Fluvial)	**?**	There are no obvious methods for determining the increase in rate of wear and tear on the pumps and associated equipment. Furthermore, the requirement will depend not just upon the increase in water volume but the impacts this has upon flooding, or potential flooding, of land requiring this increase in pump operation. Consequently, it is unlikely that this can be addressed as part of a high level national assessment without considerable additional analysis.
		(Estuary)	**?**	

2.10 Major civils

Asset			Advanced methods warranted?	
			Yes/ No	**Considerations for advanced methods**
10.1	ABUTMENT	-	**No**	
10.2	CENTRAL PIER	-	**No**	

3 Illustrative examples

C3.1: Armour layer damage

C3.2: Revetment block damage

C3.3: Protective lining stability

C3.4: Toe scour

C3.5: Channel bed scour

C3.6: Scour (outfall)

C3.7: Scour (piers and piles)

C3.8: Scour (weir)

C3.9: Displacement (flood gate)

C3.10: Displacement (weir, control gate)

C3.11: Overtopping damage

C3.12: Overflow erosion

C3.13: Overwashing (barrier beach)

C3.14: Seepage (barrier beach)

C3.15: Beach mobility (longshore transport)

PROCESS: Armour Layer Damage	C3.1

DESCRIPTION: Larger wave heights and higher water levels will result in greater loading on a structure. Cover layers are designed to be stable with tolerable (repairable damage) under certain conditions, and any exceedance of those conditions has the potential to result in an increased frequency and/or extent of damage. The displacement of the cover layer would lead to the exposure of less resistant materials below, with that deterioration of the structure leading to instability and breach if not maintained, repaired and potentially improved with a cover layer comprising larger rock or units.

APPLIES TO: Coastal and Estuary Embankments and Sloping Seawalls

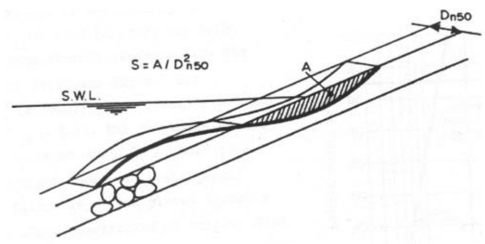
BASIC EQUATION:

$$\frac{H_s}{\Delta D_{n50}} = 0.7\,(K_D cot\alpha)^{1/3} S_d^{0.15}$$

$$A_e = S_d \cdot D_{n50}^2$$

where:

H_s = significant wave height (m)
Δ = relative buoyant density of material (i.e. for rock $\Delta = \rho_r / \rho_w - 1$) (-)
D_{n50} = representative stone size (m)
K_D = stability coefficient, Hudson formula
α = slope angle
S_d = damage level parameter = A_e / D_{n50}^2 (-)
A_e = the eroded area around sea water level (m^2)



Reference: CIRIA C683 (Section 5) The rock manual, CIRIA, London, 2007

WORKED EXAMPLE:

BASECASE: Assuming a water depth of 1.5m, with depth limited wave height of H = 1.17m approximately, and an existing cover layer stone size D_{n50} = 1.5m:

$$S_d = \sqrt[0.15]{\frac{1.17}{2.00 \cdot 1.50 \cdot 0.7\,(1.30 \cdot 2.00)^{1/3}}} = 0.053$$

$$A_e = 0.053 \cdot 1.50^2 = 0.118\text{m}^2$$

CLIMATE CHANGE IMPACT: Assuming a water level increase of 20cm, increasing water depth and enabling the depth limited wave height to rise to H = 1.33m:

$$S_d = \sqrt[0.15]{\frac{1.33}{2.00 \cdot 1.50 \cdot 0.7\,(1.30 \cdot 2.00)^{1/3}}} = 0.121$$

$$A_e = 0.121 \cdot 1.50^2 = 0.272\text{m}^2$$

COMMENT: In this example, a 20cm increase in still water level will more than double* the area vulnerable to wave damage, which would result in a need to maintain and repair damage arising over a greater area, or most likely more frequently.
**With 50cm sea level rise the area of damage in this example increases by a factor of approximately six.*

PROCESS: Revetment Block Damage — C3.2

DESCRIPTION: Revetments are designed to be stable with tolerable (repairable damage) under certain conditions, and any exceedance of those conditions has the potential to result in an increased frequency and/or extent of damage. The displacement of the revetment would lead to the exposure of less resistant materials below, with that deterioration of the structure leading to instability and breach if not maintained, repaired and potentially improved with a cover layer comprising larger blocks.

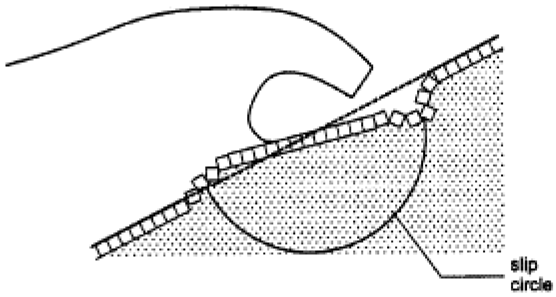
APPLIES TO: Fluvial and Estuary Embankments (Lined/Protected)

BASIC EQUATION:

$$D = \frac{0.035}{\Delta} \frac{\Phi}{\Psi} \frac{K_T K_h}{K_S} \frac{u_{cr}^2}{2g}$$

where:

D = revetment thickness (m),
Δ = relative density (-),
u_{cr} = critical vertically averaged flow velocity (m/s),
Φ = stability parameter (-),
Ψ = critical Shields parameter (-),
K_T = turbulence factor (-), K_h = depth parameter (-), and K_s = slope parameter (-)



Reference: Dikes and revetments: design, maintenance and safety assessment – Pilarczykz 1998

WORKED EXAMPLE:

BASECASE: Assuming some typical values for most of these parameters, with critical Shields parameter assuming rip-rap Ψ = 0.035, and critical vertically averaged flow velocity u_{cr} = 1m/s:

$$D = \frac{0.035}{1.40} \frac{1.00}{0.035} \frac{3.00 \cdot 1.00}{1.00} \frac{1.00^2}{2 \cdot 9.81}$$

$$D = 0.11\text{m}$$

CLIMATE CHANGE IMPACT: Assuming an increase in river flow of 15%, which comprises a 7% change in cross-sectional area and 7% increase in flow velocity, so u_{cr} = 1.07m/s:

$$D = \frac{0.035}{1.40} \frac{1.00}{0.035} \frac{3.00 \cdot 1.00}{1.00} \frac{1.07^2}{2 \cdot 9.81}$$

$$D = 0.13\text{m}$$

COMMENT: A 15% increase in river flows will also result in a 15%* increase in the required cover layer thickness for a revetment, which indicates that either the revetment will need to be upgraded to resist damage, or that maintenance and repairs will be required more frequently to address displacement and damage to the cover layer.
**With a 30% increase in river flows, the revetment thickness for stability under increased currents would need to increase by 32%.*

PROCESS: Protective Lining Stability	C3.3

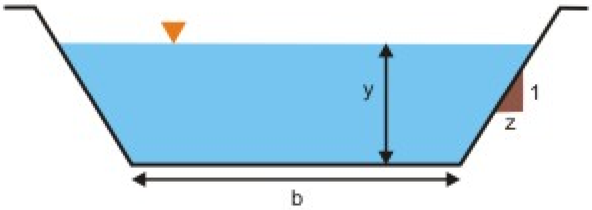
DESCRIPTION: The stability of cover layers (e.g. rip-rap) to protect embankment and channel banks are designed to accommodate particular peak flow velocities. Higher river flows may produce flow velocities that exceed the limits for the cover layer stability, rendering it inadequate and liable to greater damage/displacement.

APPLIES TO: Embankment, High Ground (Fluvial)

BASIC EQUATION:

Cover layer sizing equation

$$D_{n50} = C \cdot \frac{V^2}{g \cdot (s-1) \cdot \Omega}$$



where:

C = 0.7 (high turbulence)

V= depth-averaged velocity (m/s)

s = 2.25 (assumed specific gravity of the rip-rap)

$\Omega = \left(1 - \frac{sin\alpha^2}{sin\emptyset^2}\right)^{0.5} = 0.97$ (assuming slope angle α = 6° and friction angle ∅ = 40°)

Reference: Protection of River and Canal Banks, Section 7.6.3, RW Hemphill and ME Bramley, CIRIA, 1989

WORKED EXAMPLE:

BASECASE: For a channel with cross-sectional area of approximately 30m² and assuming flow discharge of Q = 50m³/s, flow velocity V (= Q/A) = 1.67m/s:

$$D_{n50} = 0.7 \cdot \frac{1.67^2}{9.81 \cdot (2.25-1) \cdot 0.97} = 0.165\text{m} = 165\text{mm}$$

Required minimum thickness = 1.5 · D_{n50} =250mm; typical thickness = 2.0 · D_{n50} =330mm

CLIMATE CHANGE IMPACT: Assuming a 30% increase in flow, which produces a 15% increase in flow velocity V to V = 1.92m/s:

$$D_{n50} = 0.7 \cdot \frac{1.92^2}{9.81 \cdot (2.25-1) \cdot 0.97} = 0.218\text{m} = 218\text{mm}$$

Required minimum thickness = 1.5 · D_{n50} =330mm; typical thickness = 2.0 · D_{n50} =440mm

COMMENT: In this example, a 30% increase in flow will require the thickness of the channel lining to be increased by approximately 33%. Other types of bank protection linings would need to be checked against the manufacturer's recommended velocities in individual cases of climate change flow increase, but, depending upon the choice of lining, there may be a need to modify the type of channel lining covering provided with a more robust form of protection.

PROCESS: Toe Scour — C3.4

DESCRIPTION: Larger wave heights and higher water levels (which allow larger waves to reach the shore) can result in scouring and lowering of beach or foreshore level adjacent to any structure. Depending upon the foundation/scour protection provided to the structure, this may lead to undermining and collapse of the toe to the structure. This in turn may lead to greater levels of asset damage through displacement of the primary cover layer, loss of retained fill and thus collapse of any supported structure (such as a promenade), or instability and collapse of the structure itself. There may therefore be a requirement to increase the depth of foundation or provide additional anti-scour materials to mitigate against these problems.

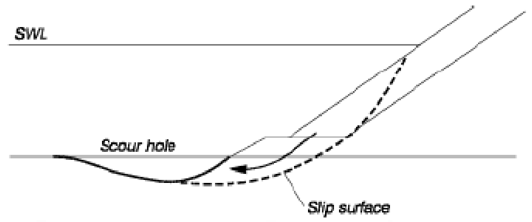
APPLIES TO: Coastal and Estuary Embankments, Sloping and Vertical Seawalls. Also other coastal structures such as Steps, Ramps and Slipways which might be undermined.

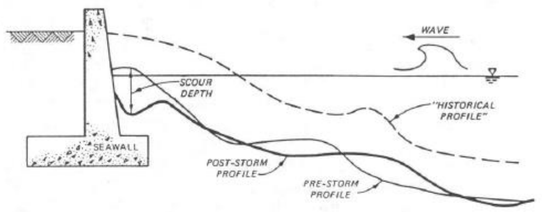
BASIC EQUATION:

$$\frac{S_m}{(H_{mo})_0} = \sqrt{22.72\frac{h}{(L_p)_0} + 0.25}$$

where:
S_m = maximum scour depth (m)
$(H_{mo})_o$ = wave height (m)
h = pre-scour water depth at the vertical wall (m)
$(L_p)_o$ = wavelength (m)

Reference: CEM VI-5–6, Coastal Engineering Manual Part VI, USACE, 2002





WORKED EXAMPLE:

BASECASE: Assuming a water depth of 1.5m, with depth limited wave height of H = 1.17m approximately:

$$S_m = 1.17\sqrt{22.72\frac{1.5}{70.0} + 0.25}$$

$$S_m = 1.00\text{m}$$

CLIMATE CHANGE IMPACT: Assuming a water level increase of 20cm, increasing water depth and enabling the depth limited wave height to rise to H = 1.33m:

$$S_m = 1.33\sqrt{22.72\frac{1.7}{70.0} + 0.25}$$

$$S_m = 1.14\text{m}$$

COMMENT: In this example, a 20cm increase in still water level will increase depth of scour by 14%*, which would result in a need to extend scour protection and, depending upon the original design, potentially increase the size of this or increase the frequency with which it is maintained and repaired to address undermining, displacement or damage arising.
**With 50cm sea level rise, depth of scour in this example increases by a factor of 33%.*

PROCESS: Channel Bed Scour — C3.5

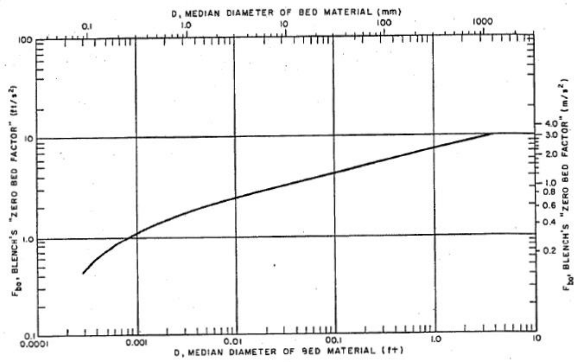
DESCRIPTION: Higher river flows can have an effect on the bed scour, particularly for non-cohesive channels. An increase of the discharge may result in an increase of the bed scour, due to an increase in the velocity producing greater bed material movement.

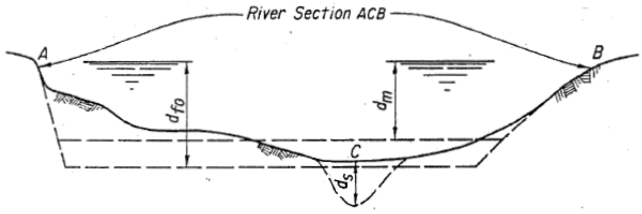
APPLIES TO: Embankments, High Ground (Fluvial)

BASIC EQUATION:

$$d_s = Z\,d_{fo} = Z\frac{q_f^{2/3}}{F_{bo}^{1/3}} = Z\frac{(Q/w)^{2/3}}{F_{bo}^{1/3}}$$

where:
d_s = depth of the scour (m)
Z = factor accounting for local flow pattern (-)
d_{fo} = water depth for zero bed sediment transport (m)
q_f = design discharge per unit width ($m^3/s/m$)
Q = discharge (m^3/s)
w = average width (m)
F_{bo} = Blench's 'zero bed factor' (m/s^2) from figure (right)





Reference: Mobile-Bed Fluviology, University of Alberta Press, by Blench T., Edmonton, Canada, 1969

WORKED EXAMPLE:

BASECASE: For an average channel width w = 19.77m, Blench's 'zero bed factor' of F_{b0} = 0.65m/s² (for a medium diameter of bed material d = 2.0mm) and flow regime right angle bends Z = 2. Baseline discharge of Q = 37m³/s:

$$d_s = 2\frac{(37/19.77)^{\frac{2}{3}}}{(0.65)^{\frac{1}{3}}} = 3.53\text{m}$$

CLIMATE CHANGE IMPACT: Assuming a flow discharge increase of 30%, resulting in a small change in average width w to 20.3m (due to sloping sides along the channel), Q = 48m³/s:

$$d_s = 2\frac{(48/20.30)^{\frac{2}{3}}}{(0.65)^{\frac{1}{3}}} = 4.09\text{m}$$

COMMENT: In this example, a 30% increase in discharge will increase the depth of the scour by over 0.5m, which is approximately 16%. This may result for example in reduction in passive pressure to sheet piling and gravity wall bank protection and therefore require works to modify the structure, or a requirement to provide additional anti-scour protection.

PROCESS: Scour (Outfall) — C3.6

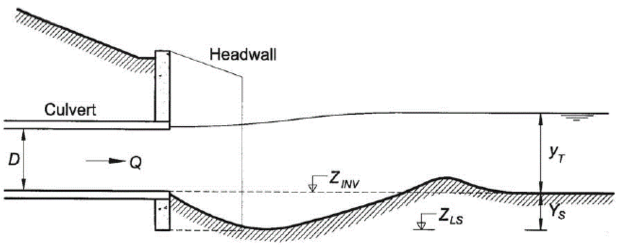
DESCRIPTION: Local scour is associated with particular local features that obstruct and deviate the flow and occurs in their immediate locality. The structures increase the local flow velocities and turbulence levels and, depending on their shape, can lead to vortices that exert increased erosive forces on the adjacent bed; changes in flows can increase the extent to which this occurs. As a result, the rates of sediment movement and erosion are locally enhanced around the structures, leading to local lowering of the bed relative to the general level of the channel.

APPLIES TO: Outfall

BASIC EQUATION:

$$Y_S = 2.07\,D\left(\frac{Q}{\sqrt{g \cdot D^5}}\right)^{0.45}$$

where:
Q = water discharge from the culvert (m^3/s)
D = the diameter of a circular culvert (m)
Y_S = depth of scour into an unprotected erodible bed (m)



Reference: CIRIA 742 (Section 5.3) Manual on scour at bridges and other hydraulic structures, second edition, CIRIA, London, 2015

WORKED EXAMPLE:

BASECASE: Assuming a pipe with diameter D = 1m, and a discharge of Q = 0.5m/s:

$$Y_S = 2.07 \cdot 1.00\left(\frac{0.500}{\sqrt{9.81 \cdot (1.00)^5}}\right)^{0.45}$$

$$Y_S = 0.91\text{m}$$

Length of scour hole *(approximately 7xYs)* ***= 6.35m***
Width of scour hole *(approximately 5xYs)* ***= 4.53m***

CLIMATE CHANGE IMPACT: Assuming a 15% increase in discharge to Q = 0.575m/s:

$$Y_S = 2.07 \cdot 1.00\left(\frac{0.575}{\sqrt{9.81 \cdot (1.00)^5}}\right)^{0.45}$$

$$Y_S = 0.97\text{m}$$

Length of scour hole = 6.76m, Width of scour hole = 4.83m

COMMENT: In this example, a 15% increase in river flows and thus discharge will result in a 13%* increase in the size of the scour hole, which indicates that the scour protection will need to be extended. It is also possible that maintenance and repairs will be required more frequently to address displacement and damage to the existing scour protection, depending upon its size and basis for its design.
**With a 30% increase in flows, the area of the scour hole increases by approximately 50%.*

PROCESS: Scour (Pier and Piles) — C3.7

DESCRIPTION: Localised scour can be induced by features that obstruct and deviate the flow, such as bridge piers or piles associated with beacons or jetties. The structures increase the local flow velocities and turbulence levels and, depending on their shape, can lead to vortices that exert increased erosive forces on the adjacent bed; changes in flows will increase those forces. As a result, the rates of sediment movement and erosion are locally enhanced around the structures, leading to local lowering of the bed.

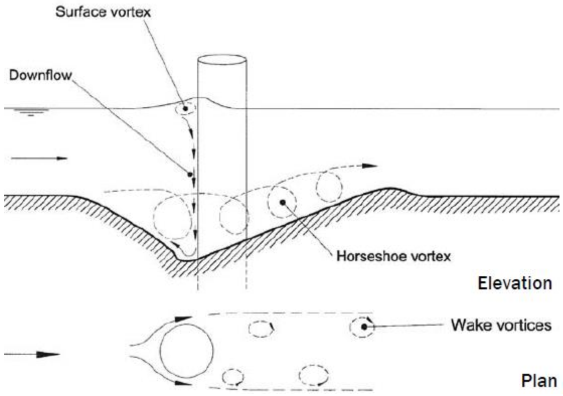
APPLIES TO: Bridge Piers, Beacons, Jetties (Estuary and Fluvial)

BASIC EQUATION:

$$Y_S = B_S \cdot \Phi_{shape} \cdot \Phi_{depth} \cdot \Phi_{velocity} \cdot \Phi_{angle}$$

where:
Y_S = equilibrium depth of scour (m)
B_S = the width of the structure measured normal to its longitudinal axis (m)
Φ = factors reported in Box 5.6 CIRIA 742, Section 5.3.3

Reference: CIRIA 742 (Section 5.3) Manual on scour at bridges and other hydraulic structures, second edition, CIRIA, London, 2015



WORKED EXAMPLE:

BASECASE: Assuming typical characteristics for various factors ($\Phi_{depth}, \Phi_{shape}, \Phi_{angle}$), with a depth-averaged velocity just upstream of the structure of 0.5m/s and threshold condition for bed material movement 1.0m/s ($\Phi_{velocity} = 0.20$):

$$Y_S = 1.00 \cdot 1.50 \cdot 0.83 \cdot 0.20 \cdot 2.71$$

$$Y_S = 0.68\text{m}$$

CLIMATE CHANGE IMPACT: Assuming a 30% increase in depth-averaged velocity:

$$Y_S = 1.00 \cdot 1.50 \cdot 0.83 \cdot 0.44 \cdot 2.71$$

$$Y_S = 1.49\text{m}$$

COMMENT: In this example, a 30% increase in depth-averaged velocity will increase equilibrium depth of scour Y_S by 120%. This may require the introduction of additional scour protection to prevent destabilisation of the structure.

PROCESS: Scour (Weir)	**C3.8**

DESCRIPTION: Local scour will occur as a result of features that obstruct flow. In the case of a weir, the plunging jet of water over the structure will produce a scour hole directly downstream of it. The size of that scour hole will depend upon the characteristics of the channel, the structure and the flows in the river. Increased flows will therefore have the potential to increase the scouring process.

APPLIES TO: Weirs

BASIC EQUATION:

$$Y_S + y_T = \left(\frac{20}{k}\right)\sqrt{\frac{q\,U_1 sin\delta}{g}}$$

where:

Y_S = the scour depth (m)

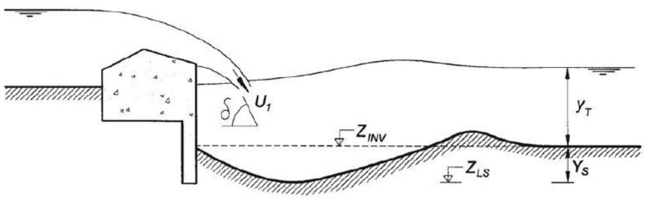
y_T = the downstream tailwater depth measured from the unscoured bed level (m)

q = the flow rate per unit width discharged by the structure ($m^3/s/m$)

U_1 = the average velocity of the plunging jet entering the tailwater (m/s)

δ = the angle between the jet and the water surface at this point

κ depends on the d_{90} size (in mm)



$\kappa = 2.95\ d_{90}^{1/3}$ for 0.1 mm $< d_{90} <$ 12.5 mm

$\kappa = 6.85$ for $d_{90} >$ 12.5 mm

Reference: CIRIA 742 (Section 5.3.9) Manual on scour at bridges and other hydraulic structures, second edition, CIRIA, London, 2015

WORKED EXAMPLE:

BASECASE: For tailwater depth y_T = 3m, velocity of the plunging jet U_1 = 1m/s, angle between the jet and water surface of 45°, k = 6.58. Assuming a baseline discharge of q = 18m³/s/m:

$$Y_S = \left(\frac{20}{6.58}\right)\sqrt{\frac{18.0 \cdot 1 \cdot sin45}{9.81}} - 3 = 0.46\text{m}$$

CLIMATE CHANGE IMPACT: Assuming discharge increases by 30%, to q = 23.4 m³/s/m and velocity of the plunging U_1 therefore increases by 10 % (U_1 = 1.1m/s):

$$Y_S = \left(\frac{20}{6.58}\right)\sqrt{\frac{23.4 \cdot 1.1 \cdot sin45}{9.81}} - 3 = 1.14\text{m}$$

COMMENT: In this example, a 30% increase in flows will increase the scour depth by over 0.5m, an increase of almost 150%. The consequence would be that the foundation of the structure may either need to be replaced to be deeper than at present to be able to accommodate that scour, or that scour protection may need to be added downstream of the structure to prevent the scour hole from forming.

PROCESS: Displacement (Flood Gate) | C3.9

DESCRIPTION: Higher water levels will lead to greater exposure of and increased forces on flood gate structures. In addition to any direct flood risk being increased, higher pressure can also lead to more vibration and damage to the structure. Two types of forces are considered here: quasi-static horizontal force and impulsive horizontal force.

APPLIES TO: Flood Gate (Coast and Estuary)

BASIC EQUATION:

$$F_{h,\ qs} = \alpha \cdot \rho \cdot g \cdot H_{mo}^{2}$$

$$F_{h,\ imp} = 15 \cdot \rho \cdot g \cdot d^{2} \cdot \left(\frac{H_{si}}{d}\right)^{3.134}$$

where:

$F_{h,\ qs}$ = the total quasi-static horizontal shoreward force (KN/m)

$F_{h,\ imp}$ = the impulsive horizontal force (KN/m)

$\gamma_w = \rho \cdot g$ = the unit weight of water = 9.81 KN/m^3

H_{mo} = the significant wave height at the toe of the structure (m)

α = an empirical coefficient = 4.76

d = the water depth (m)

Reference: Breaking wave loads at vertical seawalls and breakwaters. G. Cuomo, N.W.H. Allsop, T. Bruce and J. Pearson, 2010

WORKED EXAMPLE:

BASECASE: Assuming a water depth of 1.5m, with depth limited wave height of H = 1.17m approx.:

$$F_{h,qs} = 4.76 \cdot 9.81 \cdot 1.17^{2} = 63.92\,\frac{\mathrm{KN}}{\mathrm{m}}$$

$$F_{h,imp} = 15 \cdot 9.81 \cdot 1.5^{2} \cdot \left(\frac{1.17}{1.5}\right)^{3.134} = 151.97\,\frac{\mathrm{KN}}{\mathrm{m}}$$

CLIMATE CHANGE IMPACT: Assuming a water level increase of 20cm, increasing water depth and enabling the depth limited wave height to rise to H = 1.33m:

$$F_{h,qs} = 4.76 \cdot 9.81 \cdot 1.33^{2} = 82.60\,\frac{\mathrm{KN}}{\mathrm{m}}$$

$$F_{h,imp} = 15 \cdot 9.81 \cdot 1.7^{2} \cdot \left(\frac{1.33}{1.7}\right)^{3.134} = 197.05\,\frac{\mathrm{KN}}{\mathrm{m}}$$

CONCLUSION: In this example, a 20cm increase in water level would increase the total forces by approximately 30%. Depending upon the design of the gate, this could require more regular repair of fittings to the gate, or potentially their replacement altogether. It may even require the gate to be replaced by one with greater thickness due to the higher stress values.

PROCESS: Displacement (Weir, Control Gate)	**C3.10**

DESCRIPTION: Higher discharges will increase the hydrostatic, hydrodynamic and impact forces on an existing gated weir structure or control gate. This may occur purely from the water forces, but there will also be increased risk of impact damage resulting from debris (large logs etc.) flowing at higher velocity.

APPLIES TO: Weirs, Control Gates

BASIC EQUATION:

$$F = F_H + F_D = w\frac{\gamma_w \cdot H^2}{2} + \frac{C_d \cdot \rho \cdot V^2 \cdot A}{2}$$

where:
F = total force (KN)
F_H = hydrostatic force (KN)
F_D = hydrodynamic force (KN)
w = width gate (m)
H = depth of the water (m)
C_d = drag coefficient (-)
ρ = water density = 9.81 (KN/m^3)
A = area gate (m^2)
V = flow velocity (m^2)

Reference: 2.016 Hydrodynamics, by Prof. A.H. Techet, 2005

WORKED EXAMPLE:

BASECASE: For a width of the gate w = 3.75m, height of the gate h = 2 m, depth of the water at the gate H = 1.72m. Assuming a drag coefficient of 0.13 and a flow velocity of 1.67m/s resulting from a cross-sectional area of A = 22.3m^2 and flow discharge Q = 37m^3/s:

$$F = 3.75\frac{9.81\cdot 1.72^2}{2} + \frac{0.13\cdot 9.81\cdot \left(37/22.3\right)^2\cdot 7.5}{2} = 54.4 + 14.3 = 68.7KN$$

CLIMATE CHANGE IMPACT: Assuming a flow discharge increase of 30% to Q = 48m^3/s, which based upon the channel dimensions will also produce an increase in water depth of 10%, i.e. H = 1.88m:

$$F = 3.75\frac{9.81\cdot 1.88^2}{2} + \frac{0.13\cdot 9.81\cdot \left(48/26.8\right)^2\cdot 7.5}{2} = 65.0 + 24.1 = 89.1KN$$

COMMENT: In this example, a 30% increase in flows will increase the total force on the weir/gate also by approximately 30%. This may result in an additional maintenance to repair the gate against damage to the gate or support structure. There will also be a reduced factor of safety on the structural components, which may make them no longer code compliant and therefore requiring an upgrading of the structure.

PROCESS: Overtopping Damage — C3.11

DESCRIPTION: Larger wave heights and higher water levels will have an effect on the volume of water overtopping a structure. In addition to any direct flood risk being increased, higher rates of overtopping can also lead to more rapid deterioration of the structure. Areas of the crest and rear slope are potentially vulnerable to erosion damage from the impacts and flows resulting from overtopping waves, which can in turn lead to instability and breach if not maintained and repaired, or the structure improved by adding protection or raising.

APPLIES TO: Coastal and Estuary Embankments and Sloping Seawalls

BASIC EQUATION:

$$\frac{q}{\sqrt{g \cdot H_{mo}{}^{3}}} = \frac{0.067}{\sqrt{\tan\alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot \exp\left(-4.3 \frac{R_c}{H_{mo} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)$$

where:

H_{m0} = significant wave height (m)

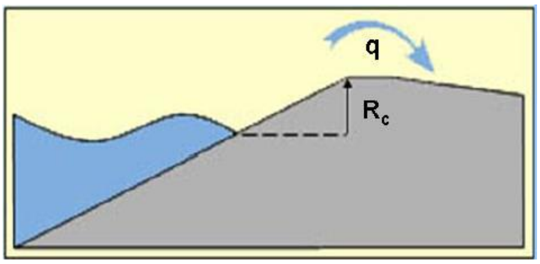
$\tan\alpha$ = slope angle (1:x)

γ_b, γ_f, γ_β, γ_v = factors for a berm, roughness, angle of wave attack, vertical wall respectively (-)

$\xi_{m-1,0}$ = breaker parameter (-)

q = mean overtopping discharge per metre length of structure(l/s/m)

R_c = freeboard (m)



Reference: EurOtop Manual (Section 5.3). Wave Overtopping of Sea Defences and Related Structures: Assessment Manual, EA, ENW, KFKI, 2007

WORKED EXAMPLE:

BASECASE: Assuming a water depth of 1.5m, with depth limited wave height of H = 1.17m approximately, and freeboard R_c=2.0m:

$$q = \sqrt{9.81 \cdot 1.17} \cdot \left[\frac{0.067}{\sqrt{0.5}} \cdot 1.00 \cdot 3.00 \cdot \exp\left(-4.3 \frac{2.0}{1.17 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0}\right)\right]$$

$$q = 0.7 \mathrm{l/s/m}$$

CLIMATE CHANGE IMPACT: Assuming a water level increase of 20cm, increasing water depth and reducing freeboard, and enabling the depth limited wave height to rise to H = 1.33m:

$$q = \sqrt{9.81 \cdot 1.33} \cdot \left[\frac{0.067}{\sqrt{0.5}} \cdot 1.00 \cdot 3.00 \cdot \exp\left(-4.3 \frac{1.8}{1.33 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0}\right)\right]$$

$$q = 4.0 \mathrm{l/s/m}$$

COMMENT: In this example, a 20cm increase in still water level will increase overtopping discharge by a factor of more than 4*, which would result in a need to maintain and repair damage arising to the crest and back face more frequently, or modify the structure by increasing the protection to those faces or raising the wall.

**With 50cm sea level rise the overtopping discharge in this example increases by a factor of nearer 40.*

PROCESS: Overflow Erosion	C3.12

DESCRIPTION: The rear (landward) faces of embankments are susceptible to surface erosion from out-of-bank overflow. Turf, or other protective layers, will be resistant to flows up to a point, but water discharging down the rear face may scour the bank and could result in lowering and cutting back of the crest, ultimately leading to a breach of the embankment. Increased water levels as a result of sea level rise or higher river flows can increase the potential for this occurring.

APPLIES TO: Embankments

BASIC EQUATIONS:

Flow velocity

$$U_{i,\ crest} = 4.5\, V^{0.3}$$

where:

$U_{i,\ crest}$ = the flow velocity on the crest for the wave i (m/s)

V = the overtopping wave volume (m^3)

Cumulative overload method

$$D = \sum_{i=1}^{500} (\alpha_M U_{i,crest}^2 - \alpha_s U_C^2)$$

for $\alpha_M U_{i,crest}^2 > \alpha_s U_C^2$

where:

D = damage number (m^2/s^2)

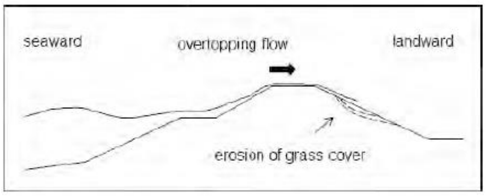
$U_{i,crest}$ = the crest velocity of overtopping wave I (m/s)

U_c = the critical velocity of the grass slope related to crest conditions (m/s)

$\alpha_M = 1 + \sin(0.5\Theta)$ load factor function of the steepness of the geometrical transition ϴ, if no transition $\alpha_M = 1$ (-)

α_S = strength factor to model the reduction of the grass strength at revetment transitions, if no transition $\alpha_S = 1$ (-)

N = the number of the waves in which $U_i > U_c$



Erosion by overtopping landward embankment

Damage numbers (D in m^2/s^2)

initial damage:	D < 500
damage at various locations:	500 < D < 1,500
failure:	D > 3,500

Reference: Flow depths and velocities at crest and landward slope of a dike, in theory and with the wave overtopping simulator, by Van der Meer et al. (2010)

WORKED EXAMPLE:

BASECASE: Assuming an overflow volume of V = 75l/s/m (270m³/h/m) for 6 hours in which $U_i > U_c$ N = 500 times:

$$U_{i,crest} = 4.5 \cdot ((270 \cdot 6)/3600)^{0.3} = 3.54 m/s$$

$$D = \sum_{i=1}^{500} (1 \cdot 3.54^2 - 1 \cdot 3.50^2) = 146 m^2/s^2$$

CLIMATE CHANGE IMPACT: Assuming an overflow volume increase of 30%, V = 97.5l/s/m (351m³/h/m) for 6 hours in which $U_i > U_c$ N = 500 times:

$$U_{i,crest} = 4.5 \cdot ((351 \cdot 6)/3600)^{0.3} = 3.83 m/s$$

$$D = \sum_{i=1}^{500} (1 \cdot 3.83^2 - 1 \cdot 3.50^2) = 1{,}215 m^2/s^2$$

COMMENT: In this example, a 30% increase in the volume overflowing the bank will increase the damage number from 146 (initial damage) to 1215 (damage at various locations). In this case, there will be an increased maintenance requirement to repair erosion on the crest and rear face of the embankment to prevent a breach from forming. Alternatively, it may be necessary to introduce protection to those surfaces under these conditions to accommodate and resist the higher volumes. Although the formula used here is based upon wave overtopping, similar principles will apply to the overflowing of river embankments.

PROCESS: Overwashing (Beach Barrier)	C3.13

DESCRIPTION: During extreme events waves will run up and overwash the crest of a barrier beach. This may result in lowering and overtopping of the barrier crest, causing damage on the back barrier, barrier rollback or even barrier breaching. Higher water levels and wave heights may increase the potential for this to occur and the magnitude of the overwash events.

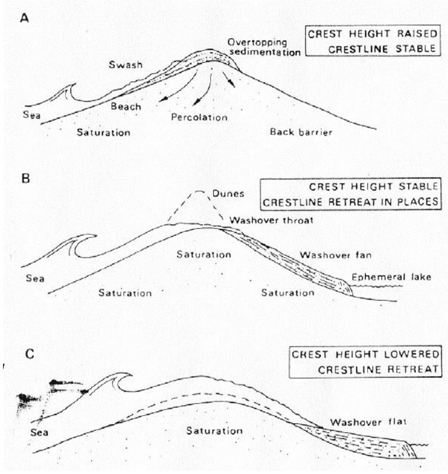
APPLIES TO: Barrier Beach (Coast)

BASIC EQUATION:

$$R_C = \frac{H_s^3}{B_a} \cdot 0.0006 \cdot (\frac{H_s}{L_m})^{-2.54}$$

where:
R_c = crest freeboard, level of crest relative to still water level
B_a = supra-tidal barrier cross-sectional area
H_s = significant wave height (the average of highest one-third wave heights)
L_m = wavelength of mean T_m period
T_m = mean wave period

Reference: Predicting breaching of shingle barrier beaches - recent advances to aid beach management, by Andrew P. Bradbury, 1998



WORKED EXAMPLE:

BASECASE: Assuming a water depth of 1.5m, with depth limited wave height of H = 1.17m approximately:

$$R_C = \frac{1.17^3}{200.0} \cdot 0.0006 \cdot (\frac{1.17}{70.0})^{-2.54}$$

$$R_C = 0.16\text{m}$$

CLIMATE CHANGE IMPACT: Assuming a water level increase of 20cm, increasing water depth and enabling the depth limited wave height to rise to H = 1.33m:

$$R_C = \frac{1.33^3}{200.0} \cdot 0.0006 \cdot (\frac{1.33}{70.0})^{-2.54}$$

$$R_C = 0.17\text{m}$$

COMMENT:
In this example, a 20cm increase in still water level will increase the level of the crest by only approximately 6%. This is a small increase, although there would be other changes to the beach profile that would affect its profile and performance, so this calculation should not be taken in isolation.
**With 50cm sea level rise the overtopping discharge in this example increases by approximately 14%.*

PROCESS: Seepage (Beach Barrier)	**C3.14**

DESCRIPTION: With higher water levels, lower beach levels and therefore greater wave loads, there is the possibility that a barrier structure will have a greater hydrostatic head after the tide has receded (tidal lag) and also that the extra ‘pressure‘ from the seaward side causes seepage through the structure.

APPLIES TO: Barrier Beach (Coast)

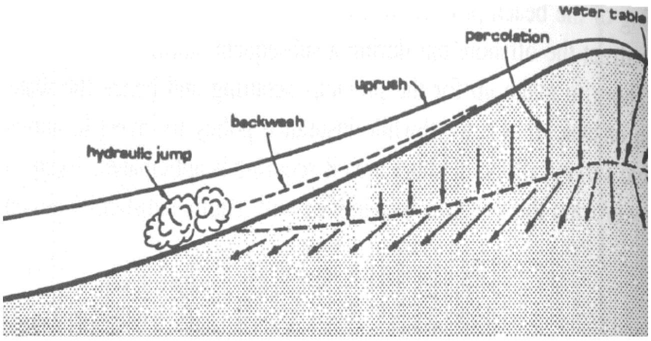
BASIC EQUATION:

$$v = k\frac{\Delta h}{\Delta l}$$

$$q = v \cdot A$$

where:
k = the permeability coefficient (m/s)
Δh/Δl = the hydraulic energy loss per unit length (-)
A = area throughflow (m^2)
q = seepage rate (m^3/s)

Reference: Les Fontaines publiques de la ville de Dijon, by Darcy, H., Paris, 1856



WORKED EXAMPLE:

BASECASE: Assuming first approximation a linear hydraulic energy loss per unit length of 0.2, and a permeability coefficient 5 x 10^{-3}m/s based on suggested ranges, and a water depth of 1.5m:

$$v = 5.00 \cdot 10^{-3}\frac{1.50}{5.00}$$

$$q = 1.00 \cdot 10^{-3}\frac{m^3}{s}$$

CLIMATE CHANGE IMPACT: Assuming a water level increase of 20cm:

$$v = 5.00 \cdot 10^{-3}\frac{1.70}{5.00}$$

$$q = 1.13 \cdot 10^{-3}\frac{m^3}{s}$$

COMMENT: A 20cm increase in sea level will result in a linear increase of the seepage rate by 13%*, which may result in instability of the landward slope and failure of the crest. This may require more maintenance activity to reprofile the bank to ensure its stability, or even a requirement to bolster it with more material imported from elsewhere.
**With 50cm sea level rise the alongshore rate in this example increases by approximately. 33%.*

PROCESS: Beach Mobility (Longshore Transport)	**C3.15**

DESCRIPTION: An increase in wave energy will result in a greater mobility of intertidal beach material, with the potential for greater longshore transport. This may occur as a result of larger waves, or higher water levels which enable larger waves to reach new areas of the beach. The implications of this extend beyond the beach to any assets which are also reliant upon the beach to provide some protection.

APPLIES TO: Beach, Barrier Beach (Coast)

BASIC EQUATION:

$$R = \frac{1.35}{2}\sqrt{\frac{g}{\gamma}\frac{H_{sb}^{\frac{5}{2}}}{tan\beta}}\sin(2\theta_b)$$

where:

R = longshore discharge (m^3/s)

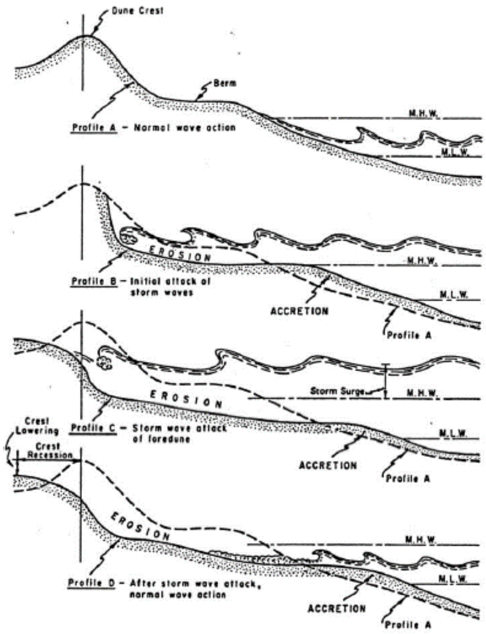
H_{sb} = significant wave height at breaking (m)

θ_b = wave height angle at breaking (°)

tanβ = bottom slope

γ = 0.78 = the constant that linearly relates depth at breaking d_b and wave height at breaking $H_b = \gamma\, d_b$

Reference: Practical considerations in longshore transport rate calculations, CETN-II-24, Coastal Engineering Research Center, 1990



WORKED EXAMPLE:

BASECASE: Assuming a water depth of 1.5m, with depth limited wave height of H = 1.17m approximately:

$$R = \frac{1.35}{2}\sqrt{\frac{9.81}{0.78}\frac{1.17^{\frac{5}{2}}}{1/30}}|\sin2(-6.0)$$

$$R = 22.10\, m^3/s$$

CLIMATE CHANGE IMPACT: Assuming a water level increase of 20cm, increasing water depth and enabling the depth limited wave height to rise to H = 1.33m:

$$R = \frac{1.35}{2}\sqrt{\frac{9.81}{0.78}\frac{1.33^{\frac{5}{2}}}{1/30}}|\sin2(-6.0)$$

$$R = 30.2\, m^3/s$$

COMMENT: A 20cm increase in water level could increase the longshore transport rate by 35–40%*, which might result in need for more frequent beach nourishment.

**With 50cm sea level rise the longshore rate in this example increases by approximately 100%, i.e. doubles.*

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