FD2628 Impact of Climate Change on Dams & Reservoirs

Final Guidance Report

May 2013

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Executive summary

This project has been carried out with the aim of providing a comprehensive, up to date review of the impact of climate change on dams and reservoirs, which takes advantage of the projections and tools that are available from UKCP09, and other research that has become available over the past few years. This report contains both an evidence based identification of the potential impacts of climate change on reservoirs and dams, and guidance that practitioners can make use of easily and quickly to provide a robust and auditable assessment of the risks of climate change and the implications it has for their strategic asset management processes.

The guidance is intended for use on dams and associated reservoirs that fall within the Reservoirs Act 1975, or may fall within the Flood and Water Management Act 2010. Although other types of man-made water bodies (e.g. ponds and storage facilities that are not raised above natural ground level) are not specifically covered, much of the guidance will be relevant to such assets. The guidance has been developed through comprehensive literature reviews, collation of nationwide information on the characterisation of dams and reservoirs, expert Panel Engineer inputs, workshops with dam Undertakers and a number of case studies that provided practical, realistic insights into the possible impacts of climate change on dams and reservoirs.

It should be noted that any guidance on climate change is, by its nature, only applicable to current levels of knowledge and understanding about climatic conditions and potential impacts. This document therefore provides a basis for risk assessment and possible adaptation given those current levels of knowledge and understanding, but stakeholders should be aware that this will change over time, and changes to guidance should be expected.

The characterisation process and workshops concluded that the most appropriate way to characterise dams and reservoirs in relation to climate change was according to their *form* (the physical makeup of the dam and ancillaries) and *function* (the operational uses of the reservoir). Overall, it was found that dam form is likely to be relatively resilient to the direct effects of climate change. There is also a well structured, well understood process under the Reservoirs Act 1975 that provides for periodic review of surveillance and maintenance requirements in a manner and timescale that is generally suited to climate change adaptation. Some reservoir functions may be relatively vulnerable to climate change, particularly where they rely on existing yields, flood flows or water quality of source waters. However, there are a number of systems that are already in place (e.g. the Water Resources Management Plan) that contain methods for identifying impacts and adapting to climate change as part of the normal ownership and operation process.

Nevertheless, dams and reservoirs and complex, large scale assets, which vary significantly in both form and function. This size, complexity and variability mean that potential vulnerabilities to climate change do exist. Often these result from separate effects on the catchment, dam structure and/or function that combine to present a specific impact mechanism or constraint for the dam or reservoir. Problems may occur due to the exacerbation of known, existing issues, but in some cases vulnerability will only become apparent over time.

The guidance set out within this document therefore concentrates on the approaches that are needed to ensure that climate change adaptation within this sector can be achieved through enhancement of the monitoring, operation and maintenance regime that already exists for the current reservoir stock. The guidance has been developed to allow dam owners to engage suitably qualified practitioners (e.g. Supervising Engineers) to carry out straightforward, periodic, risk based assessments of the impact of climate change on dams and reservoirs that are designed to fit in with the existing regulatory process. The guidance provides a practical, risk based approach for evaluating the impacts of climate change, and presents the information that is

required to carry out the assessment in easily accessible, table based formats where possible. It is also presented in a way that is intended to promote lateral thinking in practitioners.

Dams with erodible (earthfill) embankments are most likely to be vulnerable to climate change: increased erosion, more extreme fluctuations in water levels, changes in vegetation and prolonged drying during hot weather could combine to exploit existing weaknesses that may exist in the dam design or construction. The form of non-erodible structures (concrete, masonry, etc.) is unlikely to be particularly vulnerable to climate change, but there are exceptions, particularly at dams where existing climatic variation is known to cause problems associated with cracking or joint movement. Overflow structures and spillways may also be vulnerable due to increasing frequency and size of flows and catchment impacts that might increase debris and vegetation. Auxiliary structures such as valves or draw off towers may be vulnerable to similar effects and can be prone to other factors such as siltation or heat induced expansion.

Dam function can be affected in a variety of ways, including more 'obvious' impacts such as changes in hydrology or water quality, and less apparent issues such as increasing water level fluctuation leading to a deterioration in marginal vegetation conditions and hence bankside fishery functions. Such issues need to be evaluated through a combination of approaches, ranging from predictive modelling (for hydrology/yield or water quality), to trend analysis or simple analysis of change factors by operators that are sufficiently familiar with the reservoir and catchment.

Because of the variety of effects and timescales involved with climate change impacts at dams and reservoirs, the adaptation measures that have been recommended generally follow a 'plan' format, which involves an escalation of measures over time. Typically this would range from monitoring, to preventative or reactive maintenance, through to capital works and finally possible decommissioning or change of use.

In terms of the general policy and planning that surrounds dams and reservoirs, there are already a number of initiatives that are in place to reduce demand (for pubic supplies and hence seasonal storage requirements for reservoirs) and runoff during flood events, which will help with general adaptation as climate change increases stresses on form and function. Other policy areas that were identified as potentially influential to climate change adaptation include: compensation flows and discharge consents, planning controls and planning authority views on new reservoirs and reservoir extensions and land use policies that support catchment management measures.

Where new reservoirs are being planned, many of the implications of climate change relate to hydrology and demand forecasting, which are reasonably well covered through the existing guidance that has been summarised within this report. Issues such as the sustainability of secondary functions and proposed catchment management in the face of climate change also need to be considered. Considerations for the design of new reservoirs are largely covered by the risk factors that are described within this report for the existing dam stock, and the existing design standards that exist in the UK are generally sufficient and allow for the effects of climate change. In some cases reference to international standards (e.g. American Concrete Institute standard 305R - Guide to Hot Weather Concreting) may be advisable during construction if some projected climatic extremes start to be realised.

Final guidance on the implementation of the risk based approach for the regulation of dams and reservoirs, as required under the Flood and Water Management Act 2010, was not available at the time of writing this guidance, and it is strongly recommended that the guidance is renewed once it is available.

The structure and approach of this guidance have been developed to be generally compatible with the expected outputs from those reports, so their inclusion should be straightforward.

Glossary

Acronym	Meaning
AMP	Asset management period
FWMA	Flood Water and Management Act 2010
HDPE	High Density Polyethelyne
HEP	Hydro-electric power
ICOLD	International Commission of Large Dams
PET	Potential evapotranspiration
UKCP09	UK Climate Projections 2009

1. Overview

1.1 Purpose of this report

This project has been carried out following an identified need for a comprehensive, up to date review of the impact of climate change on dams and reservoirs, which makes use of projections and tools that are available from UKCP09 and other research that has become available over the past few years. The floods of summer 2007 highlighted the vulnerability of some existing dams to extreme weather and made it clear that policy makers, owners and operators need to understand how projected changes in climatic extremes might affect the existing and planned future reservoir stock in England and Wales.

The key objectives of this report are to:

- Provide an evidence based approach to identifying the potential impacts of climate change on reservoirs and dams that can underpin a risk-based approach to decisions on the actions, priorities and timescales required to respond to climate change.
- Provide guidance that practitioners can make use of easily and quickly to provide a robust and auditable assessment of the risks of climate change and the implications it might have for their strategic asset management processes.

The guidance is intended for use on dams and associated reservoirs that fall within the Reservoirs Act 1975, or may fall within the Flood and Water Management Act 2010. The Act covers both the physical infrastructure associated with the dam and auxiliary structures and those aspects of the reservoir that allow it to be used for its intended purpose (e.g. seasonal storage, flood retention etc). Although other types of man-made water bodies (e.g. ponds and storage facilities that are not raised above natural ground level) are not specifically covered, much of the guidance will be relevant to such assets.

It should be noted that any guidance on climate change is, by its nature, only applicable to current levels of knowledge and understanding about climatic conditions and potential impacts. This document therefore provides a basis for risk assessment and possible adaptation given those current levels of knowledge and understanding, but stakeholders should be aware that this will change over time, and changes to guidance should be expected.

1.2 How to use this guidance

The main purpose of the document is to provide practical guidance for stakeholders that may need to allow for climate change in the regulation, planning, design, operation and maintenance of reservoir assets. The report has therefore been structured accordingly, and the actual guidance has been separated from the reporting and background reading sections of the document. **Table 1.1 -** sets out the content and broadly intended use of each section of this guidance document. General comments on each section are as follows:

Sections 2 to 4 *are intended to provide background and reference to owners and practitioners that intend to use this document for guidance purposes.*

Section 6 *contains recommendations and guidance, which cross reference the* ***Section 3*** *charts and information notes on the impacts that can be expected from aspects of climate change that are relevant to dams.*

Section 7 *provides some of the main conclusions from the study about the potential vulnerability (and resilience) of dams and reservoirs to climate change, and the potential application of the guidance notes. It also identifies the key areas of uncertainty and future work that may be required as policy and understanding of climate change progress.*

This guidance is aimed at reservoir users, owners, operators, Panel Engineers and undertakers with a certain amount of knowledge and expertise. It is designed to be applicable to all dams and reservoirs, but the process does not have to be complex or time consuming, particularly for small, resilient assets. It is anticipated that the additional work required to carry out an assessment of the impact of climate change on dams can take as little as 1 to 3 hours depending on the size and complexity of the reservoir system. Further information is available from the Environment Agency which has published two useful guides which are available free of charge from their website.[1]

[1] 'The Owner's Guide to Reservoir Safety' and 'Working together for the safety of our reservoirs', Both published by the EA and available at http://www.environment-agency.gov.uk/business/sectors/118421.aspx

Table 1.1 - Overview and use of the guidance document

Section	Sub-section	Content	Intended use
2. Current legislation & framework	**All**	Overview of the relevant, current statutory controls on planning, design, operation and maintenance.	**Background information** on the framework that assessment and adaptation has to fit into.
3. Climate change	**3.1. Overview and application**	Introduction to climatic projections and their application to forecasts of risk and asset function.	**Background information** on the parameters described in **Section 3.2**.
	3.2. Current projections and uncertainties	Plots of projected changes to climate and hydrology plus technical notes on the impact mechanisms.	**Reference.** Should be used when carrying out the vulnerability risk assessment described in **Section 6.**
4. Development of the guidance	**4.1 Characterisation and Assessment**	Brief description of the process and rationale used to develop the format of the guidance.	**Background information** on the rationale for the structure of the guidance in **Section 6.**
	4.2 Vulnerabilities	Brief description of how the vulnerability of dams and reservoirs to climate change was assessed.	**Background information** on the content of the guidance in **Section 6.**
	4.3 Adaptation	Brief description of what is meant by 'adaptation',and how measures have been assessed.	**Background information** on the content of the guidance in **Section 6.**
5. Case studies	**5.1. Introduction and rationale**	Introduction and rationale behind the case studies that were carried out to help develop the guidance.	**Supporting guidance.** Gives examples of the sort of process that can be used to identify risks and issues.
	5.2. Key findings	Key findings from the case studies described in **Appendix D.**	**Supporting guidance.** As above
6. Guidance for stakeholders	**6.1. Planning, policy & assessment**	Evaluation of the issues that need to be considered in relation to policy considerations, or when planning for new reservoirs.	**Core guidance.** Guidance notes for regulators/legislators, planners and developers of new assets.
	6.2. Design & Construction (new dams)	Notes on the implications of climate change to design and construction of new reservoirs.	**Core guidance.** High level reference for designers of new assets or major capital works –generally refers to Section 6.3.
	6.3. Monitoring, Operation & Maintenance	Detailed, specific flow charts and guidance notes on risk assessment, monitoring and adaptation for existing reservoirs.	**Core guidance.** Main reference for owners, operators and Panel Engineers for monitoring, operation or maintenance/construction for existing assets.
7. Conclusions and recommendations	**All**	Key conclusions and recommendations for further work.	**Future development.** Provides stakeholders and policy makers with an indication of future issues or needs.

1.3 Key terms and concepts

There are a number of key terms and concepts that have been developed in relation to climate change, or have been developed specifically for this study. These are discussed in more detail in the relevant sections of the document, but a summary reference description for each term is provided in **Table 1.2** below.

Table 1.2 - Key terms and concepts

Term	Description and meaning	Where the term is used
Adaptation (pathways)	The measures (often described in a continuous plan or 'pathway') that are required at a dam or reservoir in order to reduce the vulnerability of form and function as climate change impacts are realised. The term is implicitly linked to the 'adaptation capacity' of the system - i.e. the inherent capability of the dam or reservoir to allow for changes in climate without significant change. Adaptation capacity incorporates the operational/maintenance regime as well as the physical resilience.	Section 6
Combination impacts	The additional issues that are caused when combinations of Impact Mechanisms (see below), or impacts relating to form and function combine at a dam to increase the risks posed by climate change.	Section 6
Constraints	Describe the physical processes within the reservoir that limit how it can be used for a particular function. More obvious examples include runoff/refill capacity constraining yield, but constraints such as visual appearance limiting amenity value are also included.	Section 6
Exposure	Exposure refers to the extent to which the system is subject to the weather or climate variable in question.	Section 4
Failure mode	Describes the way in which problems caused by climate can cause significant operation problems or perhaps physical failure of a particular structure (e.g. face erosion on an earthfill dam).	Section 6.3.3.1
Form	Refers to the overall 'engineering' fabric of the dam and the nature of the impervious element.	Most sections
Function	Refers to the primary and main use or categorisation of the dam-	Most Sections
Impact mechanism	Descries the way combinations of climate and climate change can affect potential failure modes at a dam (e.g. dry/hot conditions leading to loss of grass cover, followed by intense rainfall that erodes the exposed surface).	Section 6.3.3.1
Pathways	Used in this case to refer to sequential plans for adaptation (e.g. enhanced monitoring followed by changes in maintenance regime and finally capital works).	Sections 4 & 6
Resilience	The inherent capability that the dam, reservoir and catchment have to incorporate climatic changes without significant negative effects.	Sections 4 & 6
Sensitivity	"Scale of response" of a system or component to a change	Section 4
Tipping points	Refer to both sudden changes in function that can occur when impacts reach a certain level, or the effect that those changes can have when combined with non-physical factors (e.g. financial viability).	Section 6
Vulnerability	Defines the extent to which a system is susceptible to, or unable to cope with, climate change. It is a function of the sensitivity and exposure of a system to a particular weather or climate variable.	Section 6

2. Current legislation and framework

This section provides an overview of the relevant, current statutory controls on planning, design, operation and maintenance of reservoirs and their associated structures. It identifies and summarises the drivers behind the current management and operation of dams and highlights key roles and responsibilities.

2.1 Current drivers and legislation

2.1.1 Reservoirs Act 1975

The Reservoirs Act 1975 provides the legal framework to ensure the safety of UK reservoirs that hold at least 25,000 m^3 of water above natural ground level. Approximately 2,500 reservoirs are covered by the Act with some 80% of these formed by embankment dams with the remainder being concrete or masonry dams or service reservoirs. The Act is applicable in England, Wales and Scotland: it does not apply to Northern Ireland, although some reservoir owners and operators there comply with the spirit of the Act. The Act identifies four key persons or organisations with distinct functions and responsibilities as follows:

Undertakers: are generally the owners or operators of the reservoir and have ultimate responsibility for the safety of the reservoir. They include water companies, navigation authorities, the Environment Agency, the Ministry of Defence and other reservoir users such as sailing and fishing clubs, and private landowners. Reservoirs owners must appoint a Panel Engineer (a specialist civil engineer who is qualified and experienced in reservoir safety) to continuously supervise the reservoir (Supervising Engineer) and carry out periodic inspections (Inspecting Engineer).

Enforcement Authorities: The Enforcement Authority is responsible for ensuring that the Undertakers observe and comply with the requirements of the Act. Since 1 October 2004 the Environment Agency has been the Enforcement Authority for England and Wales. The Enforcement Authorities in Scotland are the Local Authorities.

Qualified Civil Engineers (also referred to as Panel Engineers): Qualified Civil Engineers are experienced reservoir engineers appointed to one of the panels under the Act by the Secretary of State in consultation with the Institution of Civil Engineers. They are responsible for the design and supervision of construction, the supervision of measures in the interests of safety, inspection of reservoirs and the ongoing supervision of reservoirs.

Secretary of State: The Secretary of State is responsible for overseeing the activities of the Enforcement Authorities, appointment of Qualified Civil Engineers and making statutory instruments to prescribe regulations. Current responsibility for the Act in England lies with the Secretary of State for Environment, Food and Rural Affairs. Since July 1999, the Scottish Parliament and the National Assembly for Wales have had the powers to make specific regulations for Scotland and Wales respectively and Scotland is currently in the process of passing its own legislation in relation to reservoir safety.

The accidental, uncontrolled escape of water from an impounding or other reservoir can threaten life and property. Greater security is required against dam failure where there is a severe threat of loss of life and extensive damage and a lower security where the threat is less severe. All dams should be assessed for the consequences of failure, and the categories shown in **Table 2.1** indicate the potential effects of dam failure for each of the categories A to D. Further details are available in the "Institution of Civil Engineers Report 'Floods and Reservoir Safety',1996,3rd edition".

Table 2.1 - Dam category and potential effect of a dam breach

Dam category	Potential effect of a dam breach
A	Where breach could endanger lives in a community*.
B	Where a breach could: (i) Endanger lives not in a community or, (ii) Result in extensive damage.
C	Where a breach would pose negligible risk to life and cause limited damage.
D	Special cases where no loss of life can be foreseen as a result of a breach and very limited additional flood damage would be caused.

*A community in this context is considered to be 10 or more persons.

2.1.1.1 Section 10

Section 10 (1) of the Reservoirs Act 1975 requires Undertakers to have a periodical inspection of any reservoir by an Inspecting Engineer. The Inspecting Engineer is appointed for a limited period, and they only act on the day of the inspection and during the period of the preparation and issue of the Report and Certificate. Under section 11 (2), the Construction or Inspecting Engineer should give directions about the information that is to be recorded. This is a particularly important responsibility of the Construction/Inspecting Engineer as this is where they give directions regarding the Undertakers' responsibilities for visual inspection of the reservoir and the monitoring instrumentation to be used. Timings of the visits should be varied from year to year to ensure that the reservoir is observed during different seasons or follow, if possible, extreme events such as heavy rainfall. The extent and type of monitoring may need to be amended to reflect the vulnerabilities and hazards to the dam or reservoir caused by climate change. Although this guidance does not specify which Panel Engineer should carry out the formal climate change reviews, recommendations for changes to monitoring must be reviewed and agreed with the Inspecting Engineer.

2.1.1.2 Section 12

Under the Reservoirs Act 1975, an annual Statement by the Supervising Engineer is required under Section 12 (2). There is no format given for the annual statement although guidelines are provided. The frequency of the examinations can be recommended by the Inspecting Engineer although it is up to the Supervising Engineer to decide when and how frequently they should visit the dam. This guidance recommends that the monitoring and maintenance activities that have been implemented as a response to potential climate change should be reviewed as part of the Supervising Engineer's periodic visits.

2.1.2 Flood and Water Management Act 2010

The Flood and Water Management Act (FWMA) introduces new arrangements for reservoir safety based on risk rather than the size of the reservoir. Reservoirs with a capacity between 10,000 and 25,000 m^3 will be brought within the scope of the Reservoir Act. The Flood and Water Management Act 2010 updates the Reservoirs Act 1975 and promotes a more risk-based approach to regulation and engineering assessment of reservoirs. **This means that all undertakers with reservoirs with a capacity over 10,000m^3 must register their reservoirs and must prepare a reservoir flood plan**. Guidance has yet to be issued over how this risk based approach might be defined, but current indications are that most reservoirs that pose a risk to life or property will be included within a risk assessment system that is similar to the current framework. **Because of this, the risk assessment approach that has been adopted within this guidance is based along the principles contained in the Reservoirs Act 1975.**

2.1.3 Reservoir flood plans

Reservoir flood plans are designed to ensure arrangements are in place so that emergency services can respond effectively if there is an uncontrolled release of water from a reservoir. Although the requirement to produce on-site plans will not come into effect until ministerial direction is issued, the Environment Agency is recommending their completion. Further details and guidance can be found on the Environment Agency website, http://www.environment-agency.gov.uk/business/sectors/125353.aspx. Reservoir flood plans include: an on-site response plan, which is the responsibility of the Undertaker; an inundation plan, which is produced and maintained by the Environment Agency; and an off-site response plan which is maintained by the Local Resilience Forum (LRF).

3. Climate change

3.1 Overview and application

3.1.1 Summary of potential effects

The climate change effects that are reviewed within this chapter have been targeted to provide guidance that is relevant to the potential impacts that have been identified for form and function in Chapters 4 to 6. A summary of these effects, along with a high level assessment of the potential change that is anticipated over the 2050 – 2080 horizon is provided in **Table 3.1** below. Details of the derivation and quantification of each of these effects is provided in the following sections.

Table 3.1 - Summary of relevant climate change effects

Potential climate change variable or effect	**Level of climatic change predicted**
Rainfall – daily maximum	Significant increase
Rainfall – storm return period	Winter: significant (more frequent events) Summer: not significant
Rainfall - average	Significant (winter and summer)
Flows	Winter: significant increase Summer: significant decrease
Temperature	Significant increase
Snowfall	Significant decrease
Wind	Not significant
Potential Evapotranspiration (PET)	Significant increase
Groundwater levels	Variable (according to area/aquifer)
Water demand	Significant increase
Water quality	Variable, but generally significant
Vegetation growth rates/growing season	Significant increase
Demand for heating and cooling (hydropower energy)	Winter decrease, summer increase – overall impact is variable but may not be significant
Climatic stress on vegetation (trees, peat, grasses)	Potentially significant (change in species mix)
Pests/invasive species	Potentially significant increase
Stress and disease risk for humans	Potentially significant
Fish/aquatic parasites	Variable; significant for some species

3.1.2 Climate change projections and UKCP09

Information about climate change relies largely on the modelling of global climate and the perturbation of such models to account for future changes in greenhouse gas emissions. Projections of climate change are produced using General Circulation Models (GCMs) and commonly downscaled to higher resolution Regional Climate Models (RCMs). The UK Climate Change Projections 2009 (UKCP09) provide a combined assessment of the projections from a number of GCMs, which have been combined with a range of estimates from the Met Office's own model, to provide a set of probabilistic climate change projections. For a complete explanation of the UKCP09 methodology, readers are referred to the UKCP09 Climate Change Projections report (Murphy *et al*., 2009).

A wide range of information is provided with UKCP09:

- Probabilistic projections of climate change over land,
- Probabilistic projections of climate change over marine areas,
- Projections of trends in storm surges,
- Projections of sea-level rise,
- A Weather Generator tool for producing synthetic meteorological timeseries.

Probabilities are presented in probability density functions (PDFs) and cumulative distribution functions (CDFs) (see examples in **Figure 3.1**). The shape of the PDF reflects the higher relative probability of projections falling towards the middle of a range, with fewer results towards the tails. A CDF is a cumulative version of the PDF, which can be used to read off the appropriate projection for different percentiles. For example, in **Figure 3.1b,** the projections show that the 'central estimate' (i.e. the 50th percentile, or median) is 20%, i.e. it is as likely that the change will exceed 20% as it is that it will not. For the ends of the tails of the CDF, the 10th percentile shows that there is only a 10% chance that there will be no increase (i.e. a 90% chance that the increase will be greater than 0%), and the 90th percentile shows that there is only a 10% chance that the change will exceed 40%.

UKCP09 is driven by three of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) emissions scenarios – B1, A1B and A1FI – described as Low, Medium and High emissions respectively (see Nakićenović & Swart (2000) for more details). Projections based on these three scenarios are provided at 25km grid squares, also for 16 administrative areas, 23 river basins, and 6 marine regions for the coastal waters of the UK (**see Figure 3.2**).

Figure 3.1 – Example of UKCP09 projections in the form of (a) a probability density function, and (b) and cumulative probability function

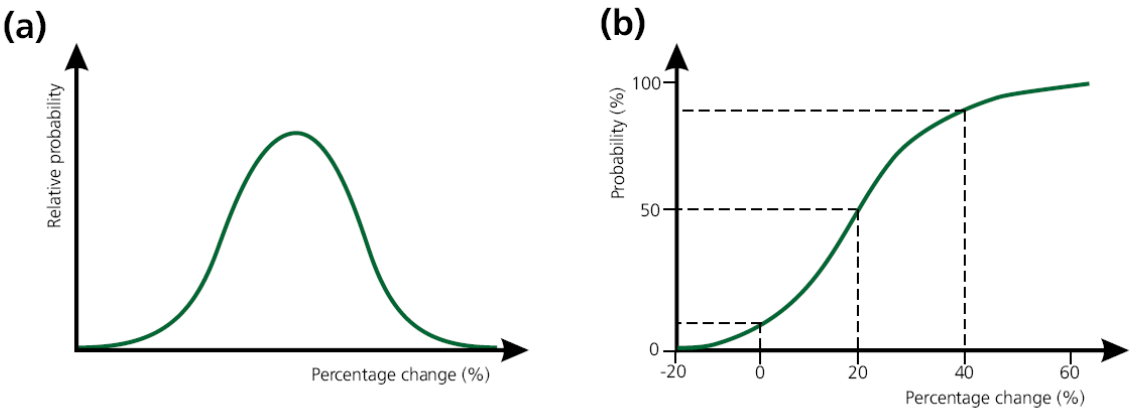
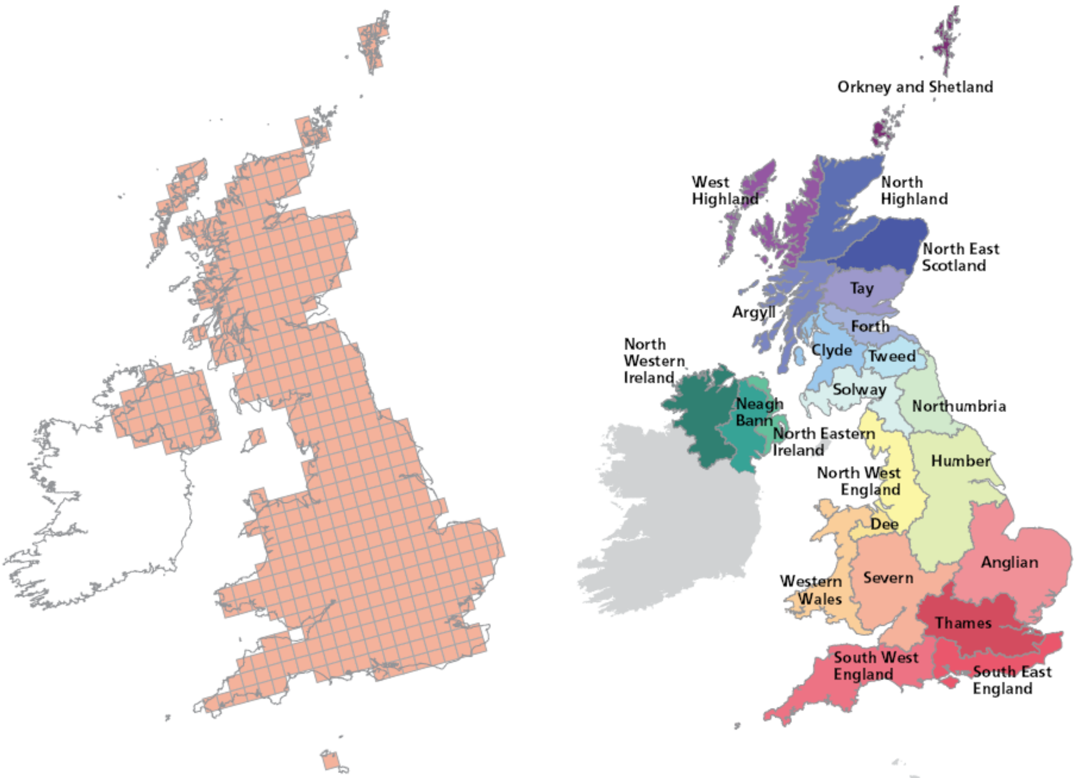


Figure 3.2 – UKCP09 areas over which probabilistic projections are available. Left: 25km grid squares; right: 23 river basins (Jenkins *et al*., 2009)



Projections are presented for seven overlapping 30-year ‘timeslices’ which move forward in decadal steps (i.e. 2010–2039, 2020–2049, etc. until 2070–2099). The projections provide absolute future data (averaged across the 30 years within the timeslice) expressed as either relative (percentage) or absolute changes, depending on the climate variable.

3.1.3 Application of UKCP09

3.1.3.1 Direct Application of UKCP09

For simple assessments it may be possible to directly apply outputs of UKCP09 based on the absolute values or relative changes provided within the forecasts. For example, an erodible dam could be sensitive to rainfall erosion of the dam face. UKCP09 can be used to identify the level of change that might result in annual, seasonal mean and extreme rainfall, and from this a high-level assessment of the change in risk can be made based on the level of change in comparison to the baseline conditions. Guidance on direct application is provided in **Section 3.2**.

This direct application of UKCP09 data is most suited to simple assessments, either where sensitivity only relates to one climate variable or where an initial review indicates that potential sensitivities can be managed through simple adaptation measures (e.g. enhanced monitoring or changes in pro-active maintenance). Where impacts are potentially large, require accurate forecasting in advance or relate to more complex combinations of climate change effects, then more advanced models (as described below) are likely to be required.

It is also possible to directly apply other data, e.g. various projects have projected changes in median and Q95 flow, and these changes could be used as 'flow factors' to gain a quick impression of what flows may be like in future. These are also provided in **Section 3.2.** Again, the level of risk and impact needs to be considered when using these simpler approaches.

3.1.3.2 Perturbation and Modelling

For a more detailed assessment, climate and other data can be used for perturbation and modelling. Models that have suitable climate related inputs can be used to evaluate the potential impacts of climate change. Applications primarily include water resource modelling, water quality impact assessment and flood forecasting (including evaluation of peak flows over overflow structures). The outputs from such models can then be used for other applications – e.g. more detailed assessments of likely changes in reservoir levels.

The most common approach to modelling is to perturb climatic sequences to simulate potential climate change. A perturbation refers to the application of climate change to a baseline (observed) series of data. Two issues of scale are important in a perturbation. Firstly, the baseline and model control *timescales* should be similar; the data being perturbed should cover a similar timespan to the control period, otherwise the impacts of climate change can be under or overestimated (scaling can be used, but this is complex). Secondly, the *spatial scale* is important; change factors are calculated from climate or other models (e.g. hydrological models) which will likely be at a different scale, or even a different location, to the point or area of interest. Appropriate downscaling of climate model data is important but certain processes may not be captured, so these uncertainties should be explicit. Similarly, the application of flow factors from donor catchments needs to ensure catchment similarity.

Perturbation generally involves the application of monthly mean changes in variables. This method is quick to apply and widely used but only reflects changes in the mean; changes in extremes are not captured. Therefore, if extremes are of particular interest, other methods should be considered, e.g. more sophisticated perturbation approaches, use of climate model output or Weather Generator output as inputs to impact models.

Alternatively, climatic sequences can be replaced by output from climate models or from weather generators. This allows users to explore extremes and natural variability. However, models may require re-calibration, or data may need to be standardised as there is often some bias between the control period of climate models and observations (which are 'corrected' in a perturbation by applying a change factor).

3.2 Current projections and uncertainties

3.2.1 Overview of projected changes (2080)

All projections used in this report are from UKCP09. The projections are presented with reference to the twelve river basins wholly or partly in England and Wales (see Error! Reference source not found.). All projections refer to the 2080s timeslice.

Rainfall. In broad terms, the UKCP09 projections indicate an increase in rainfall in winter months and a reduction in summer; on an annual basis rainfall totals are expected to change little. However, extreme precipitation is expected to increase (see **Section 3.2.2.2**).

Temperature. Projections for mean summer temperature show a trend towards higher values. Under Low emissions, increases of 2.8°C (1.2 to 5.1) are projected, and under High emissions, projections show increases of 4.7°C (2.3 to 8.2). Changes in summer daily maximum temperature show an increase of 3.7°C (1.0 to 7.7) for Low emissions and 6.0°C (2.3 to 11.8) for High emissions.

Snowfall. Probabilistic projections of changes in snowfall were not produced as part of UKCP09. However, non-probabilistic projections can be taken from the raw RCM data. Projections for the change in winter snowfall by the 2080s are for 80-100% reduction for England and much of Wales under the Medium emissions scenario.

Wind Speed. UKCP09 does not contain probabilistic projections of wind speed; instead, as with snowfall data, non-probabilistic projections can be taken from the raw RCM output. According to the UKCP09 Projections report (Murphy et al., 2009), the wind speeds produced by the RCM do not validate particularly well against current climate, but the percentage changes between baseline and future are expected to be robust. The RCM projected changes are small – predominantly a change of up to -3% for most of the UK but are consistent with evidence from GCMs (Murphy *et al*., 2009).

3.2.2 Climate change data

For complex modelling assessments users can generate full generated weather sequences using the online Weather Generator. The Weather Generator can be accessed via the UKCP09 User Interface (http://ukclimateprojections-ui.defra.gov.uk/ui/admin/login.php). Registration is required, but access is free.

The UKPP09 Weather Generator produces 'synthetic' timeseries of baseline and future daily and hourly weather conditions for 5km by 5km grid squares across the UK. The data are described as 'synthetic' because they do not represent predictions of future weather for specific dates but simulate weather conditions that could occur, consistent with natural variability and the UKCP09 projections. As such, the Weather Generator is a valuable resource, providing a unique source of spatially detailed, hourly or daily synthetic weather data for the whole UK, both for the historical baseline (1961-1990) and for future timeslices. Running the Weather Generator requires some knowledge of the UKCP09 climate projections, and there is information on this, along with a User Interface manual, on the UKCP09 website. The Threshold Detector allows users to set particular thresholds (e.g. the number of days above 25°C).

Most of the evaluations of the impact of climate change on dams and reservoirs will not require complex modelling, and higher level assessments can be carried out based on summary information that has been generated from previous climate change studies. This guidance contains the following summary data for climate change:

- Plume plots for various climate parameters (Section 3.2.2.1),
- Areally distributed plots of rainfall changes (Section 3.2.2.2),
- Information on changes in flows and yield (Sections 3.2.2.3 to 3.2.2.5),
- Other changes (Section 3.2.2.6).

3.2.2.1 Plume plots

Plume plots illustrate how climatic variables might change over the course of the twenty-first century at a given map location. In order to avoid excessive data plots only the high emissions scenarios have been represented. This presents a suitably conservative view for resilient assets such as dams and reservoirs. Plots are presented in **Appendix B** for the following climate variables:

- Mean summer precipitation,
- Mean winter precipitation,
- Mean winter wettest day precipitation,
- Mean summer temperature,
- Mean winter temperature,
- Mean summer average daily maximum temperature.

Results are grouped according to the 6 river basins, which have been selected to give a good regional representation of the nationwide variation in factors (note that plots for all river basins are available online). The basins that have been used are:

- South West England,
- Thames,
- Anglian,
- Severn,
- Northumbria,
- North West England.

Reasonably representative values can therefore be obtained from the plume plots for any area of interest in England and Wales.

3.2.2.2 Rainfall changes (2080 Summary)

Projections for winter rainfall are for increases of 16% (2 to 43) under Low emissions and up to 26% (4 to 74) under High emissions. Corresponding projections for summer rainfall show a change of -14% (-36 to 3) under Low emissions and -26% (-59 to 1) under High emissions.

The larger percentage changes in winter precipitation tend to be found in the more southerly areas, particularly southeast England, southwest England and the Thames basins but also western Wales and other coastal areas (see **Figures 3.3 and 3.4**). For summer precipitation, southern areas generally experience the largest declines (see **Figures 3.5 and 3.6**).

Extreme precipitation is classified in UKCP09 under projections for the average ‘wettest day of the season’ and, as with mean precipitation, is quantified as percentage changes from the baseline. Projections for winter show increases in extreme rainfall events, increasing by 13% (0 to 38) under Low emissions and 21% (0 to 62) under High emissions. As with mean precipitation, changes tend to be larger towards the southern UK but also towards the east (e.g. southeast England, Thames and Anglian), with the smallest changes in more northerly areas (see **Figures 3.7 and 3.8**).

Figure 3.3 – UKCP09 Mean winter precipitation projections for the 2080s under Low Emissions. Left to right: 10th, 50th and 90th percentiles. © Crown copyright 2009

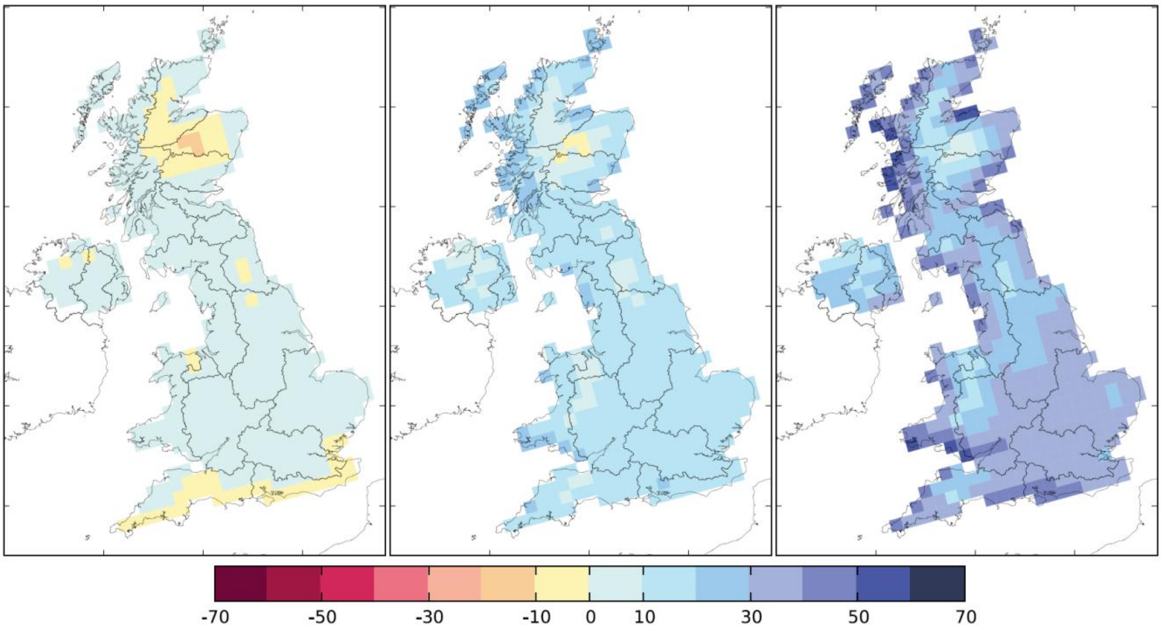


Figure 3.4 – UKCP09 Mean winter precipitation projections for the 2080s under High Emissions. Left to right: 10th, 50th and 90th percentiles. © Crown copyright 2009

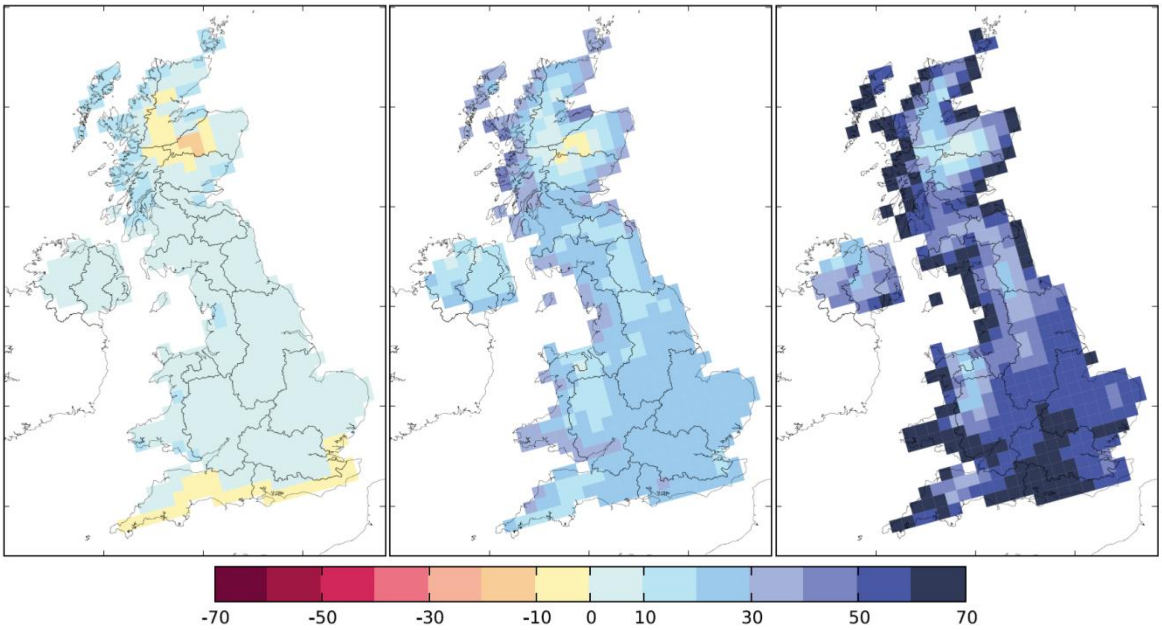


Figure 3.5 – UKCP09 Mean summer precipitation projections for the 2080s under Low Emissions. Left to right: 10th, 50th and 90th percentiles. © Crown copyright 2009

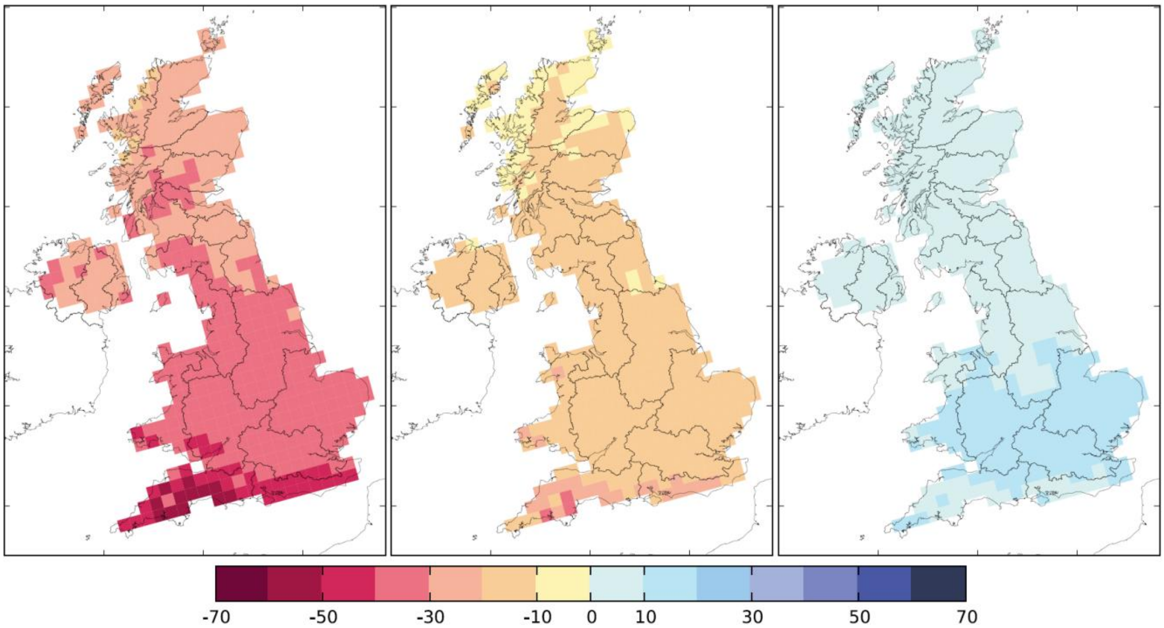


Figure 3.6 – UKCP09 Mean summer precipitation projections for the 2080s under High Emissions. Left to right: 10th, 50th and 90th percentiles. © Crown copyright 2009

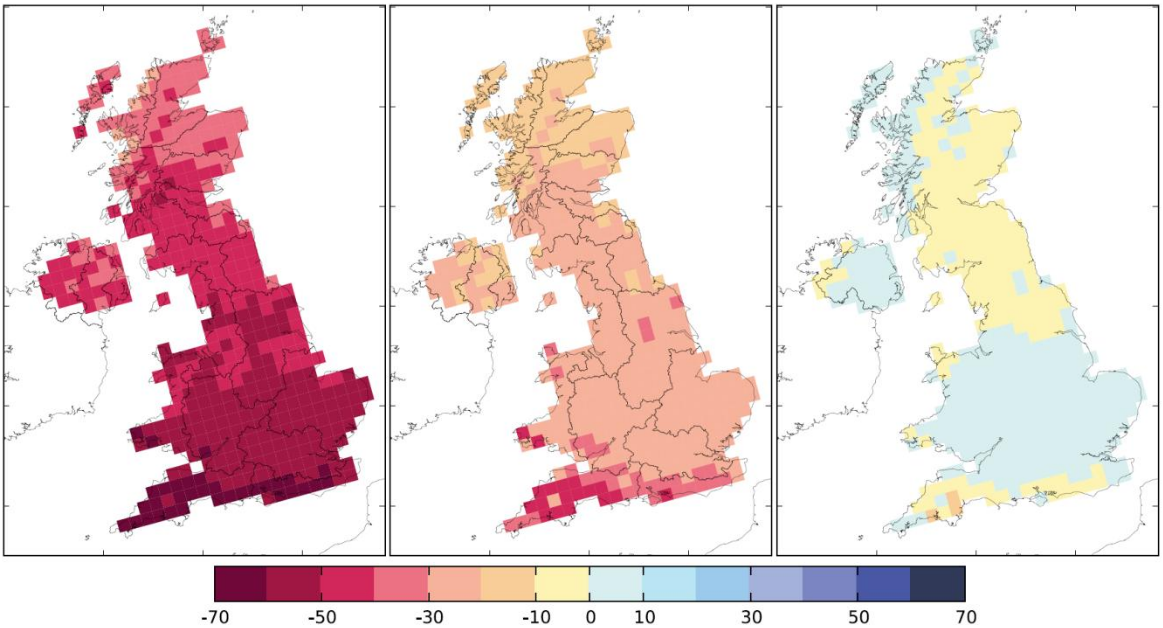
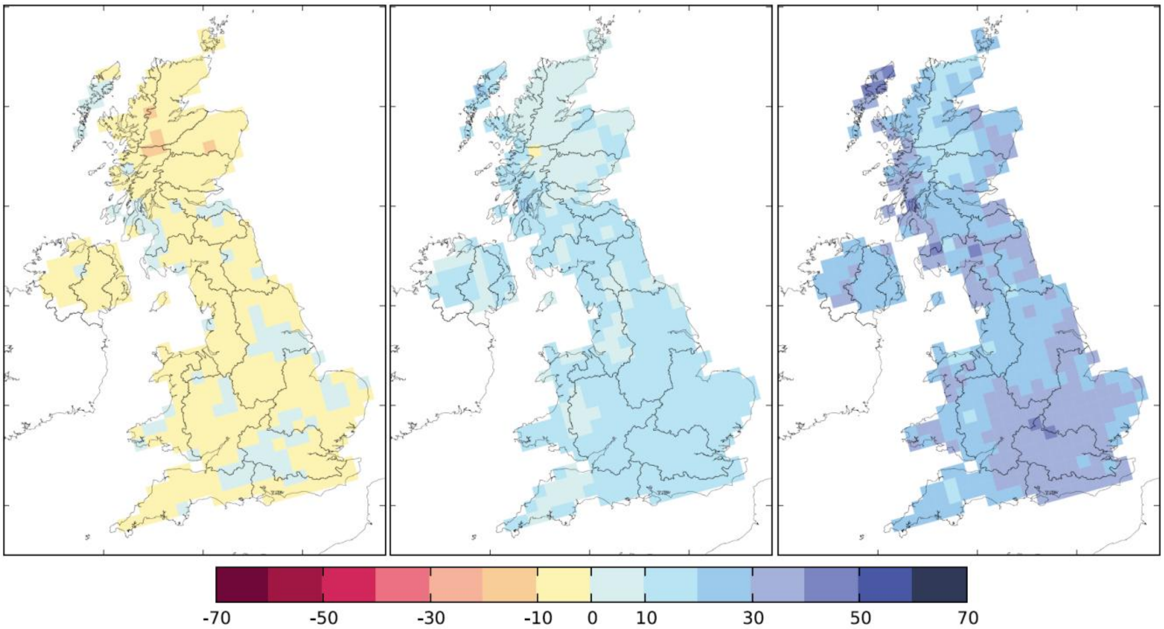
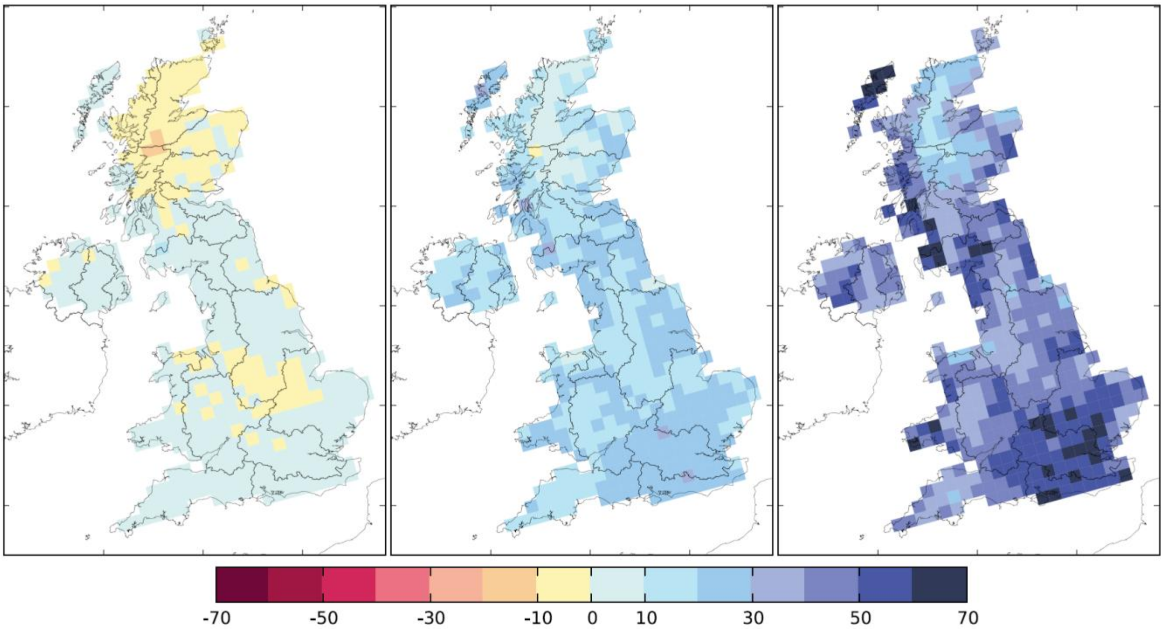


Figure 3.7 – UKCP09 winter Wettest Day projections for the 2080s under Low Emissions. Left to right: 10th, 50th and 90th percentiles. © Crown copyright 2009



Figure

Figure 3.8 – UKCP09 winter Wettest Day projections for the 2080s under High Emissions. Left to right: 10th, 50th and 90th percentiles. © Crown copyright 2009

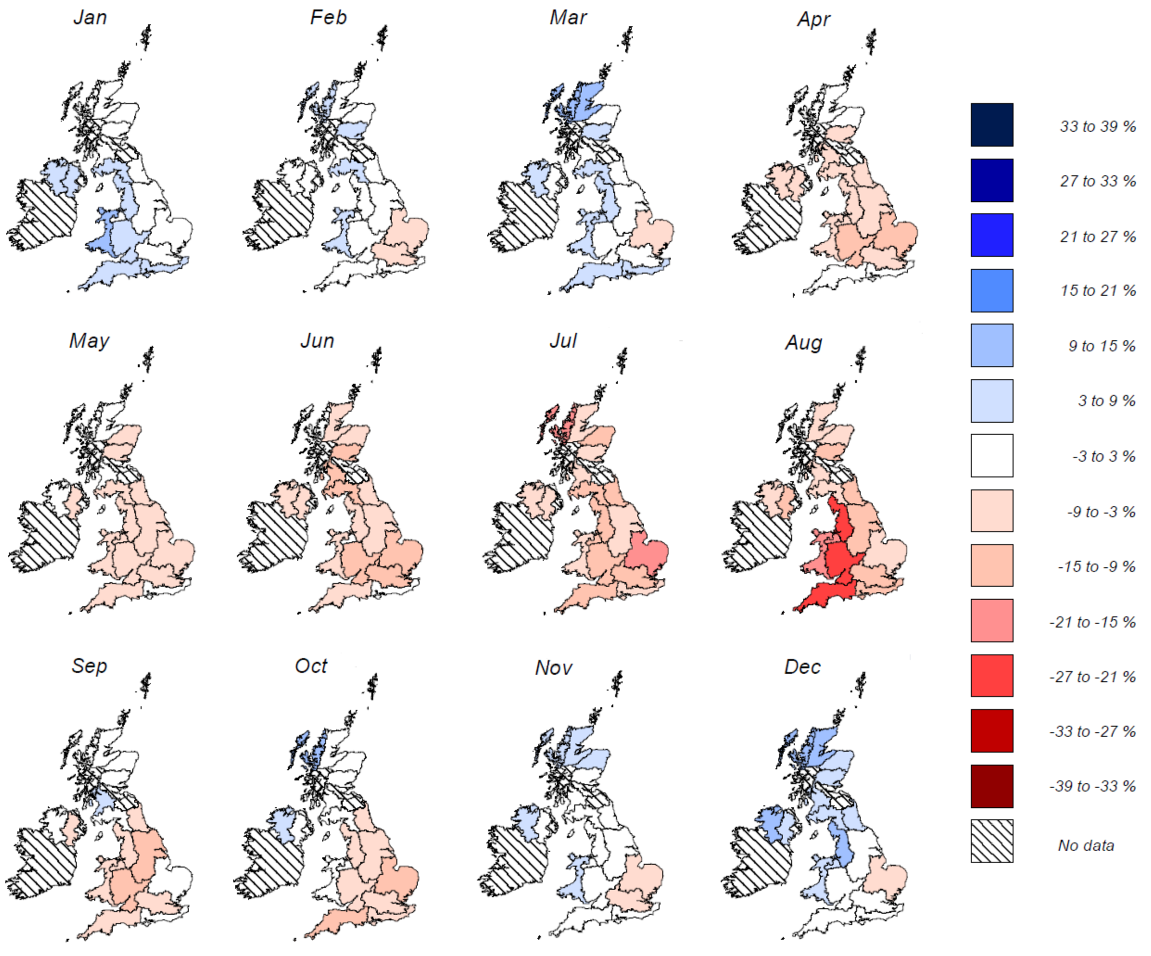


3.2.2.3 Flow changes

In this section we present information from an UKWIR study as well as results from the Future Flows project[2].. .

The UKWIR (2009) study modelled 70 catchments, although this only assessed the 2020s and Medium emissions. **Figure 3.9** shows how the central estimates (projections at the 50th percentile of climate change and hydrological model outputs) of river flows are projected to change when the results of the model catchments are averaged across the UKCP09 river basin areas. The figures show that all river basins experience a reduction in flows in the months April to August (inclusive), and reductions continue into September and October for all basins in England and Wales. The most severe reductions are found in western basins in August (up to a 33% reduction). During winter months, most basins in England and Wales are projected to experience a negligible change or a small increase in flows.

Figure 3.9 – Central estimates of changes in flow for UKCP09 river basin-averaged areas for the 2020s under Medium emissions (UKWIR, 2009) © UKWIR 2009

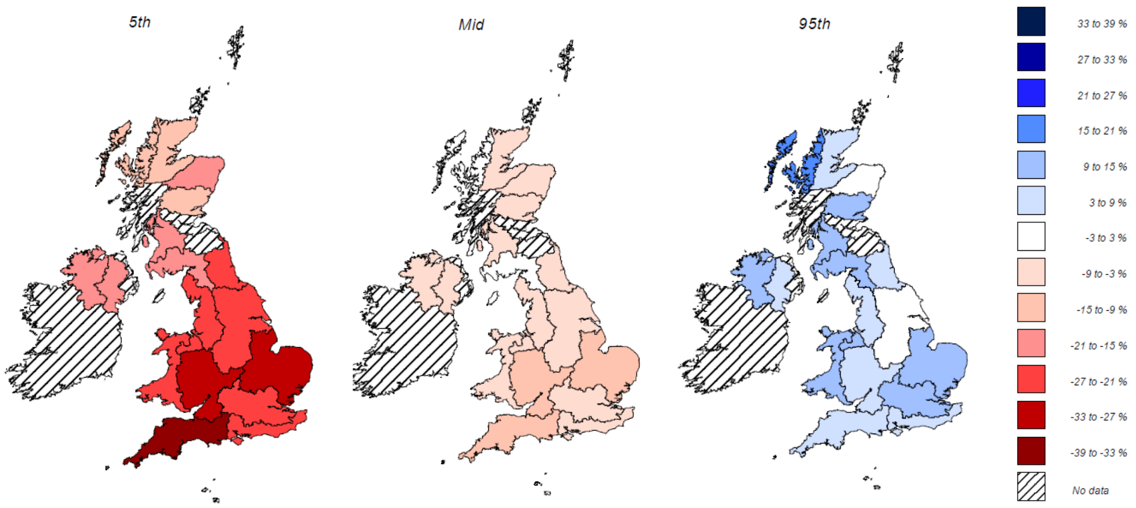


Q95 refers to flows that are exceeded 95% of the time and is often used as a metric for assessing how low flows may change in rivers. **Figure 3.10** shows how Q95 flow is projected to change in the UKCP09 river basins by the 2020s under Medium emissions. The 'Mid' projection shows all basins in England and Wales experiencing a reduction in Q95 flow of up to 15%. At the tails of the

[2] Funded by the Environment Agency of England and Wales, Defra, UK Water Industry Research, the Centre for Ecology & Hydrology, the British Geological Survey and Wallingford Hydrosolutions.

probability distribution, it can be seen that the reductions could be as high as 39% (South West England in left-hand map) or show an increase of up to 15% (see the right-hand map).

Figure 3.10 – Change in Q95 flow for UKCP09 river basin-averaged areas for the 2020s under Medium emissions – at 5th, 50th and 95th percentiles (UKWIR, 2009) © UKWIR 2009



Partial information is also available for the 2050s High emissions scenario for four rivers which have results broadly representative of their respective basins (see **Table 3.2;** results from the UKWIR CL08 project). These show more significant reductions than for the 2020s, particularly for Q95 in South West England.

Table 3.2 - Percentage change in flow for Q50 and Q95 for the 2050s High Emissions scenarios for four English river basins

River	Basin	Q50			Q95		
		10th	50th	90th	10th	50th	90th
Manifold at Ilam	Humber	-18	-7	3	-32	-16	0
Kennet at Theale	Thames	-18	-8	5	-32	-16	-2
Ribble at Arnford	North West England	-14	-3	11	-27	-12	1
Tamar at Gunnislake	South West England	-27	-12	-1	-71	-36	-10

The Future Flows (and Groundwater Levels) Project provides an 11-member ensemble projection of daily river flow time series (1951-2098) for 282 rivers in Great Britain. The following is a summary[3] of results for the 2050s Medium emissions for mean flow, Q10 (higher flow, exceeded 10% of the time) and Q95:

- **Mean annual flow** changes are mainly within +/-20 % with large areas suggesting +/-5% changes. For about half of the scenarios, small increases are showed, concentrated in the south and east, while for the majority of the scenarios the west will see a reduction of mean annual flow up to -40%. In Scotland, simulations suggest no changes or a reduction in mean annual flow.
- **Q10** changes are within +/- 20% for most Great Britain and ensemble members, although the geographical pattern between increase and decrease is complex and varies. Some larger changes (up to increase of 60%) are suggested for the midlands for two scenarios

[3] Edited summary from http://www.ceh.ac.uk/sci_programmes/Water/Future%20Flows/FFRiverFlowChanges-2050s.html

and for East Anglia and southern England for one scenario each. Conversely, reductions up to 40% are only suggested by one scenario but across most of Eastern England. Changes in across most of Scotland tend to remains within +/- 5% for 7 scenarios but to increase up to 20% for two scenarios.

- **Q95** is projected to decrease anywhere in Britain according to all but 2 scenarios with small increases in the east and/or centre. The magnitude of decreases is variable, however, with areas such as northwest Scotland and northwest England showing little change for 2 scenarios, to reductions of up to 80% in Wales and northwest England for up to 3 scenarios. Most scenarios however do not suggest reductions to exceed 60%.

Data for each of the 282 modelled rivers can be downloaded via the CEH website[4], along with the climate data used to drive the models. In addition, for some sites wider information is provided based on a subset of the full UKCP09 projections.

The most accurate way to assess potential hydrological changes for a specific catchment or point of interest is to model the impacts using a catchment-specific, calibrated and validated model. If the catchment is not included in the UKWIR or Future Flows analysis, it may be possible to infer the changes based on catchment similarity, but new hydrological modelling using perturbed or alternative inputs would be required to support significant decisions.

3.2.2.4 Flow changes: extreme high flows

Extreme high flows can be classified into two categories:

- **Probable Maximum Flow (PMF)**. There is limited research on this, but work by Collier and the FREE programme (Collier 2009) indicates that there could be some increase. Currently research is not robust enough to include as guidance values.
- **Other high flows**. Environment Agency (2011) guidance provides indicative sensitivity ranges for peak rainfall intensity and change factors for extreme river flows which can be used for small (<5km^2) and large catchments respectively. For small catchments and urban/local drainage sites, the guidance recommends that where projection of future rainfall is required for events more frequent that those with a 1 in 5 year chance of occurrence, information is taken from UKCP09, and that for rarer events, changes to rainfall presented in Table 3.3 are used. For larger catchments, regionalised change factors (including upper and lower end estimates) are provided for the 1 in 50 year return period flow (a High++ scenario is also provided). It is recommended that the change factors are used for outline risk assessments and where this indicates that climate change could lead to expensive or long lead-time adaptation measures, that hydrological modelling is then undertaken for specific catchments, particularly those that are not covered by recent datasets such as UKWIR (2009) and Future Flows.

Table 3.3 - Change to extreme rainfall intensity compared to a 1961-90 baseline

Applies across all of England	Total potential change anticipated for 2020s	Total potential change anticipated for 2050s	Total potential change anticipated for 2080s
Upper end estimate	10%	20%	40%
Change factor	5%	10%	20%
Lower end estimate	0	5%	10%

[4] http://www.ceh.ac.uk/sci_programmes/Water/Future%20Flows/FFGWLProductsandDatasets.html

Guidance on the impact that climate change might have on return periods, and hence the frequency at which large flows can occur, is less certain, although the Environment Agency (2011) guidance recommends applying a constant (regional) change factor for extrapolations beyond the 1 in 50 year return period provided. Nevertheless, it is important as this will dictate how often flood retention reservoirs will fill and how often spillways will operate. It is therefore recommended that guidance on rainfall return periods is used as a proxy. One source is Sanderson (2010). This project modelled return period variation for 40 cities across the UK, and assessors could use this document if they require an idea of details and uncertainties. For winter, all extremes were projected to become more frequent in the future (their return periods are smaller than present-day return periods). However, the change in summer extremes is much less certain and should probably be discounted for the purposes of this guidance. **Although there is variation and uncertainty, the general rule of thumb is that winter return periods will reduce by around 40% by 2050 (i.e. 1 in 100 becomes 1 in 60, 1 in 5 becomes 1 in 3) and be halved by 2080.**

For summer, there was relatively little variation shown in return periods, and currently it should be assumed that these will remain constant with respect to climate change. Therefore, although magnitude is anticipated to increase in relation to the guidance provided above, storms are unlikely to become more frequent (it is acknowledged that there is overlap between return period and magnitude, but it is recommended that these are kept separate for the purpose of simplicity).

3.2.2.5 Reservoir yields and water levels

General guidance on reservoir yields and water levels is difficult as this will depend on the water balance (including flows, abstraction and demand) for the individual reservoir. For Water Undertakers, the process of evaluating the impact of climate change on yield assessment is included within the Water Resources Management Plan guidance which is updated every 5 years. Currently the process usually involves rainfall-runoff modelling to produce perturbed flow sequences, which in turn are used to derive future yield assessments. These can be used to determine how quickly reservoirs will be drawn down during drought events and indicate how levels are likely to fluctuate in future compared to current operation.

This process is complex and time consuming but well understood by the Water Undertakers. Where a simpler approach is required, assessors can either apply existing water balance models using average monthly flow changes (available from UKWIR (2009) project or pre-processed for selected months in Future Flows) or use the average of the 50th percentile Q50 and Q95 values shown in **Table 3.2** as a proxy measure (similar values are available for Future Flows) to give an indication of the level of reduction in yields that could be expected by 2050. This is really only applicable to smaller reservoirs or reservoirs where winter refill is not constrained (i.e. it is effectively ‘guaranteed’ to fill every year).

3.2.2.6 Other changes

UKCP09 does not contain projections for every climate-related variable that might be of interest to dam and reservoir owners and operators. **Table 3.4** contains a summary of such variables, including:

- A brief description of the potential changes for England and Wales,
- Details of where further information can be obtained,
- How the variables could be modelled to account for climate change.

More in depth information for some of the variables is provided in **Appendix A.**

Table 3.4 - Summary of changes in other variables

Variable	Potential change	Application, further information and modelling approaches
Wind	Projected changes are small, although there are uncertainties.	Modelling approaches not likely to be needed (assume wind speeds remain similar to current climate). Further information in Murphy *et al*. (2009).
Potential Evapotranspiration (PET)	Increases in all months. Larger percentage increases in winter, but larger absolute changes in summer and autumn. See regional plume plots for temperature changes **(Appendix B)** as simple approximation.	Modelling approaches not likely to be needed except for river flows (where **Section 3.2.2.3** should be used), or specific groundwater models. Monthly and seasonal changes based on UKCP09 output are provided in UKWIR (2009) for Catchment Abstraction Management Strategies (CAMS) regions in the UK for the 2020s.
Groundwater	Higher levels in winter and spring; lower in summer and autumn. Amount of change depends on the aquifer and local factors; simple 'rules of thumb' cannot be applied.	Simple application not possible. UKWIR CL04 project (UKWIR, 2007) provides some further information on modelling approaches. Recharge and groundwater models can be used (as described in UKWIR, 2007).
Water demand	Domestic demand could increase by 1.8%–3.7% by the 2050s. Irrigation demand may increase by as much as 30% depending on the region.	For simple assessments use the values provided. The CC:DeW report (Downing *et al*., 2003) contains results for each Environment Agency region. The results focus on average demand; changes in peak demand are likely to be larger. These could be assessed using an appropriate demand forecasting model.
Water quality	Greater sedimentation associated with storm events, particularly after prolonged dry periods where soils become very dry and loose. Uncertainty regarding nutrient concentrations reflecting the complex balance between leaching and dilution. However, an increase is likely during reservoir refill after prolonged dry periods. Increased risk of algal blooms in summer as a result of lower level, more stagnant water with nutrient-rich inflows associated with storm events. Also an increased risk of cynobacteria. Increase in Dissolved Organic Carbon (and colour) due to larger or more frequent high flows. Increase in water temperature leading to increases in pH and reductions in Dissolved Oxygen (DO). DO is also affected by increases in nutrients and collapse of algal blooms. Increase in concentration of metals during storms after prolonged dry periods. Increase in concentrations due to low flows if point source pollutants occur within the catchment.	Methods for assessing changes are very site specific. The UKWIR CL08 project (forthcoming) will provide some information, but direct translation is not possible. For simple assessments the following guidance can be used: a) The key risk for turbidity, metals and diffuse nutrients relates to heavy rainfall after dry periods. Therefore, the percentage changes in rainfall intensity and average rainfall (for months that are known to cause problems for water quality) can be used to assess the degree of impact. b) Algal blooms are difficult to predict. Use increase in growing season and increase in summer temperature to give percentage indication of likely change. Algae risk may increase if phosphate concentrations are currently below limiting limits and increased rainfall intensity increases nutrient loads into source waters (e.g. from sewage or farms). c) For DO, saturation decreases with temperature, but the relationship is not linear. For UK summer events the relationship is approximately $DO = Pc/35+t$, where DO is in mg/l, Pc = air pressure related constant, t = temperature (ºC) , In other words, for a change of 20ºC - 21ºC DO reduces by around 2%. Climate change is therefore likely to directly reduce DO during 'sags' by around 5% - 15%. The impact of nutrients and algal blooms needs to be considered in addition to this. d) Most other point source pollutants can be considered in terms of concentration effects – i.e. concentrations are directly proportional to

Variable	Potential change	Application, further information and modelling approaches
		decreases in flow rates (unless inputs vary according to season or rainfall). Where more accurate forecasts are required, then catchment-specific water quality models (e.g. INCA or SIMCAT) should be used.
Growth rates / growing season	Enhanced growth rates (except where limited by moisture, nutrients or competition). Lengthening of the thermal growing season for all of the UK by at least a month and up to three months in the southeast resulting in year-round thermal growing conditions (2080 conditions).	Use 2080s changes as a primary indicator. UKCIP02 scenarios (Hulme *et al*., 2002) give further indicative information. The UKCP09 Weather Generator can be used to investigate the variability and change in these variables for sites across the UK; use threshold indicators via the user interface if thresholds on growing conditions are known.
Heating and cooling in buildings (electricity demand)	Decreased requirement for winter heating; increased requirement for summer cooling. Driven by number of 'heating degree days' (HDD) and 'cooling degree days' (CDD) (see **Appendix A** for details).	Maps of baseline HDD and CDD are provided in **Appendix A**. Some outline values for changes are provided in Appendix A, but the UKCP09 Weather Generator can also be used to investigate the variability and change in heating and cooling degree days for sites across the U.K. (using threshold values).
Climatic stress on trees, peat, grasses	Alder vulnerable to *Phytophthora*; beech, birch, elm, larch and Sitka spruce become less suitable, especially in the south and east. Grasses are generally resilient although may be vulnerable to compaction from saturation following very heavy summer rainfall events. Ombrotrophic bogs are likely to be vulnerable because seasonal rainfall variability is likely to increase and in particular they may dry out in summer.	Extensive details and maps of tree vulnerability during climate change are provided in **www.forestry.gov.uk/fr/climatechangeengland**. This should be used for assessment. For other details, see Ray *et al*. (2010) and Bisgrove and Hadley (2002).
Invasive species	Increased vegetation growth and warmer winters could favour invasive species. Reservoirs can be hot-spots for invasive species.	Risks are quite specific and owners would need to consult specialist literature such as Rahel and Olden (2008); Parrott *et al*. (2009) for details. In general it is advised that owners maintain contact with regulators and find out if there are any risks nearby whenever update reviews are being carried out.
Pests and plant diseases	Warmer conditions are likely to make pests more prevalent due to a quicker life cycle and the ability to overwinter as adults. Some diseases will thrive in wetter winters (e.g. *Phytophthora*) or drier summers (e.g. powdery mildew); others may decline. Particular impacts are likely on drought vulnerable (e.g. beech) or pest/disease specific species (e.g. horse chestnut).	See guidance for forestry above. Further information is contained in Bisgrove and Hadley (2002). Additional guidance is provided in **Appendix A.**
Stress and disease risk for humans	Heat exhaustion and heat stroke potentially a problem in hotter summers; malaria unlikely to become a problem, but conditions could favour West Nile virus.	Details of heat stress calculations are provided in **Appendix A.**
Fish parasites	No specific guidance is available. However, anecdotal evidence indicates that problems associated with some species (e.g. fish lice) are related to the duration of warmer water in the reservoir. This will be exacerbated by warmer winters.	Use increases in growing season (above) and mean winter temperatures to give an idea of how water temperatures might change and hence how problems may increase.

4. Development of the guidance

To develop the guidance the following approach and methodology was used:

- **A characterisation assessment** system for dams and reservoirs was developed to use as the basis for further evaluation and identification of current and future impacts of climate change.
- Potential, generic, **vulnerabilities and adaptation measures** were identified and then refined using a risk assessment framework.
- Workshops and then case studies were carried out to produce an evidence base for the types and significance of the vulnerabilities that might occur and the approaches that might be adopted to implement suitable adaptation measures.

4.1 Characterisation and assessment

For the purposes of developing the guidance, a number of methods for characterising dams and reservoirs were considered and mapped. This included assessments of size, ownership and regional variation, but ultimately the workshop assessments indicated that the most appropriate was to characterise dams according to their **form** (i.e. physical makeup) and their **function** (i.e. use). This characterisation has been chosen as it allows consideration not only of the impact of climate on dam components, but also on the system in which the dam operates. Indeed although distinct, form and function are related and do affect each other. This is reflected in the **Section 6** guidance. **Table 4.1** provides details of the initial characterisation that was carried out for form and function.

Table 4.1 - Form and function type – initial characterisation

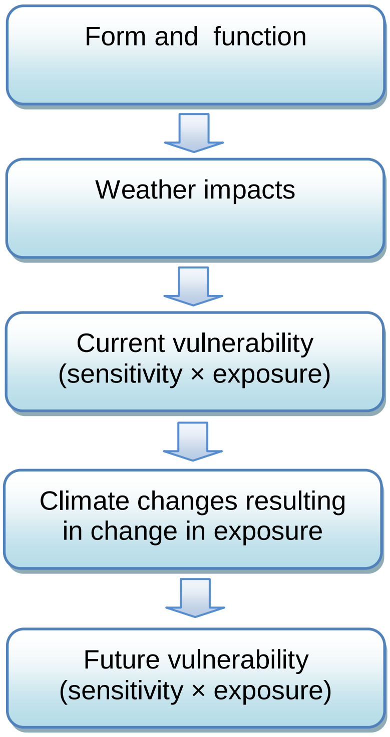
Form types	Function types
Embankment: erodible-clay core	Seasonal storage for water supply
Embankment: erodible - homogeneous	Flood retention
Embankment: erodible-other impermeable element	Recreation
Embankment: non-erodible (concrete/masonry)	Fisheries/ecology/wildlife
Overflow structures (all)	Hydropower
Ancillaries	Other (including effluent storage)

Following the case studies and workshops, it was decided that there are multiple potential designs for erodible embankments, and that these should be considered within a single characterisation. The differences between erodible embankment designs have been addressed through the consideration of impact mechanisms, as described in **Section 6**.

4.2 Vulnerabilities

A ‘generic ‘vulnerability assessment was carried out to identify the current and potential vulnerability of dams and reservoirs to weather and climate and was used as guidance for the workshops and case studies. The assessment was structured around dam form and function following the results of the characterisation. The approach taken to evaluating generic vulnerability is summarised in Error! Reference source not found..

Figure 4.1 - Vulnerability assessment methodology



This process allowed a 'long list' of potential vulnerabilities to be condensed into a risk weighted, reasonably short list that could then be used to support the case studies and development of the guidance.

A summary of the 'short list' of potential and current vulnerabilities to dams and reservoirs form and function that were considered during the case studies is included for reference in **Appendix C**. These summary tables provide a broadly based, theoretical assessment of how dam form or function may be impacted by climate change and how the vulnerability may or may not increase as a result.

One of the key findings of this assessment was that vulnerabilities to form and function can be linked (e.g. where reservoir level fluctuations change in response to function, this affects risks and impacts on the embankment). This has been reflected in the concept behind the guidance in Section 6.

4.3 Adaptation

Climate adaptation can be defined as the "process, or outcome of a process, that leads to a reduction in harm, risk or harm or realisation of benefits associated with climate variability and climate change"(Willows and Connell 2003;111). There are a wide range of adaptation measures that can be implemented but these are very dependent on the adaptive capacity of the system, i.e. how easily the system can be altered to accommodate change. For example, an embankment may be vulnerable to erosion around crest or face structures, which could be exacerbated by cycles of wetting and drying due to climate change, leading to more significant problems such as core desiccation or even slumping failure during flood events. However, this might be simply addressed by improved crest drainage, changes in grass cutting or by excluding livestock. If the actual design or material of the embankment presents a piping risk that that may be exacerbated by increased winter rainfall and hence fill frequency, it is likely that extensive adaptation in the form of remedial capital works would be required.

As with vulnerability, the process for assessing potential adaptation measures started by identifying the ‘generic’ measures that might be applied to dam form and function. These were split into a number of categories covering:

1. Policy, planning and assessment,
2. Design and construction,
3. Operation and maintenance.

Details of the generic adaptation measures are provided in **Appendix E and Appendix F** and practical application of adaptation requirements is discussed in **Section 6**.

As described in **Section 6**, the adaptation and review process needs to be based on an identification of the elements of the dam that might be vulnerable to climate change with a summary plan of how these risks should be managed for that particular structure.

5. Case studies

5.1 Introduction and rationale

The objective of the case studies was to practically identify how vulnerabilities might present themselves for a variety of dams and how the management regime associated with the reservoir and structures might affect adaptation responses. A structured interview approach was identified as the most suitable method of reviewing the dams and reservoirs within the case studies, as this was able to cover both the available technical information and practical, anecdotal information about existing vulnerability to climatic variation. The interview process included a review of the existing management and maintenance regime, collation of historic issues associated with climatic variation, and a qualitative, risk based evaluation of the potential impacts of climate change might have on the form and function of the asset(s).

The case studies identified a series of adaptation measures for each reservoir with a particular emphasis on how these may fit in with the existing operations and maintenance regime. It also identified and examined the issue of combination impacts – i.e. how climatic variations could combine at a dam or reservoir to cause problems that might not be immediately obvious when single impact mechanisms are considered. For example, a spillway may be able to cope with increased peak flows, but not if it becomes blocked due to increased debris caused by climate related changes in the catchment.

As the case studies were primarily geared towards identifying practicalities and recorded or anecdotal information, all case studies were carried out on existing assets, although implications of vulnerabilities on planning and design of new dams were also considered during some of the discussions. The case studies were selected to cover as many aspects of form and function as possible. The size of dam and type of owner, as well as the geographical location was also considered during selection. **Table 5.1** provides a summary of the type, size, form and function of the reservoirs investigated.

Table 5.1 - Summary of form and function of studied reservoirs

Reservoir / dam case study number	Class	Form	Primary function	Size
1	A	Clay core earth fill embankment	Public water supply (primarily offline)	Large
2a and 2b	C/D	2a:silt clay embankments 2b:earth fill embankment	Private fisheries (impounding)	Small Small
3	A	Earthfill puddle clay core	Public water supply (impounding)	Large
4	A	Cyclopean masonry with secondary earthfill	Public water supply (impounding)	Large
5	Various	Clay silt "informal" embankments	Flood storage (offline)	Various
6	A	Clay core with masonry spillway	Seasonal storage for water supply only (impounding)	Medium
7*	A	Buttress dam	Seasonal storage for water supply only (impounding)	Large
8	C	Semi compacted homogeneous bunded dam	Flood storage (offline)	Small
9	B	Semi compacted homogeneous bunded dam	Flood storage (offline)	Medium/Large
10	A	Compacted homogenous fill	Flood storage (impounding)	Large
11	A	Cyclopean masonry	Seasonal storage for water supply, hydropower and recreation (impounding)	Large

*discussions also covered a wide range of other dam assets owned by the organisation, with an emphasis on anecdotal information about potential climate change impacts on form.

5.2 Key findings

Discussion and details around the 11 case studies are presented in **Appendix D.** A summary of some of the key findings that were not identified in the generic vulnerability and adaptation assessments are presented in **Table 5.2** below.

Overall it was found that the form of the dams is, in most cases, inherently resilient to the effects of climate change, provided that the dam and ancillaries are well engineered with an appropriate factor of safety. However, vulnerabilities do occur. These vulnerabilities tend to be specific and often result from complex, interconnected effects that occur as a result of specific weaknesses in the form, or impacts on function that can then place the form at risk. The guidance has therefore been developed to try and encompass these complexities and relationships, but the case studies showed that when evaluating impacts any assessor needs to:

- For form, be professionally trained and experienced with dams in general and preferably have an existing knowledge of the dam that is being reviewed.
- For function, be experienced in how the dam operates and how the Undertaker organisation manages the functioning of the dam.
- Think laterally. Impacts are often not related to single issues and risks will be missed if the assessor does not consider the dam and reservoir in a holistic sense.

Table 5.2 - Key case study findings not identified through the generic assessments

Feature	Finding	Effects that need to be considered in guidance	Recommendations for adaptation	Case study reference
General	Many of the vulnerabilities that were identified related to mechanisms that are not caused by climate change but manifest or are exacerbated by climate change.		Need to consider combination impacts between climate change and reservoir vulnerability.	All reservoirs.
Planning	The reservoir catchment is often key to the assessment and vulnerable to changes in land use.	Impacts resulting in increased flows into the reservoir, increased sedimentation, landslips etc which can cause a series of impacts such as overtopping, contamination, blockages etc.	Catchment condition, type and vulnerability should be considered at all stages of reservoir missing word? from planning and design through to operation and maintenance.	3: Historic landslips in catchments. 5: Changes in land use. Groundwater dominated catchments (Environment Agency case study). 6: Historic movement of catchment.
Design, operation and maintenance	Vegetation encroachment on dam embankments or near ancillaries makes maintenance more difficult and prevents adequate management of burrowing animals.	Not directly related to climate although it presents a key impact mechanism for core desiccation or piping. Vermin issues occur more frequently in heavily farmed lowland areas with good vegetation cover.	Ensure adequate vegetation management can take place.	5: Burrowing is a particular problem. 10: Some abutment damage due to moles.
	Quality and depth of topsoil and surface protection is a key factor in the resilience of the dam to erosion issues during and following drought periods. It provides a good indicator of the risk of climate change for erosion or desiccation of earth fill dams.	Increased risk of erosion following loss of grass due to drought or waterlogging.	Review topsoil and surface protection requirements during design and future operation. Check condition particularly following drought periods. Consider modifications to grass maintenance activities.	1: Evidence suggests that for many other reservoirs in the south east insufficient cover is an issue. 5:Grass cover on embankment is poor leading to core desiccation. 6: 8: Land use within catchment changes regularly and has caused some issues (livestock poaching, bare patches around crest and penstock due to cattle grazing). 7 (additional discussions), 10

Feature	Finding	Effects that need to be considered in guidance	Recommendations for adaptation	Case study reference
	Widely varying vulnerability of different types of jointing in pitching or masonry to climatic effects.	Increased vulnerability to erosion or failure due to joint movement, fluctuating water levels and increased rainfall. Degradation of exposed stone benches etc.	Consider resistance of materials to temperature increases and sunlight (avoid large expanses of asphalt, polysulphides etc). Consider increased exposure of materials.	3: Deterioration of jointing leading to unstable pitching. 4: Masonry cracks leading to increased risk of failure. 5: Exposure of pitching.
	Vulnerabilities of dam form to erosion, piping or desiccation are often found in areas where material types or engineering causes concentration of effects – e.g. wave action on areas where formal pitching meets informal beaching, areas around structures where erosion or drainage concentration occurs etc.	Primarily rainfall or runoff or wave related erosion risk, can also act as the starting point for internal embankment failures (piping, slumping etc).	Make sure these are considered in the review as they are likely to represent some of the key vulnerabilities.	1, 5, 6, 8: Land use unsuitable for form leading to risk. 10: Some erosion of access track caused by rainfall.
	Disease or drought stress caused by climate change may cause trees or vegetation on or adjacent to embankments or in catchments to become vulnerable to uprooting during high wind and storms. Other issues such as waterlogging of trees in occasional reservoir footprints also increase vulnerability.	Particular issue is the risk that the health of trees and other large vegetation may be damaged by drought/disease prior to large storm events that then cause treefall or problematic debris within the reservoir. Blockage of spillways or draw off towers etc.	Review and consider types of trees and susceptibility to drought, disease and storm conditions (including erosion of root bowl by rainfall).	1. 5: Vegetation control is problematic and causes damage. 10: Sinkhole development.
	Variation of water levels in the reservoir is a key driver for potential impacts. Can expose areas or cause problems with cycles of loading or unloading.	Driver for exacerbating multiple issues e.g. erosion, embankment failure.	Consider effect of climate change on frequency and extent of level variation in the reservoir.	1, 3, 5, 6, 8-10

Feature	Finding	Effects that need to be considered in guidance	Recommendations for adaptation	Case study reference
	Dam may no longer be suitable for designed or secondary function due to changes in operation caused by climate change. As a result, the form of the reservoir may become more vulnerable to damage.	General increase in form vulnerability due to modifications in operation of dam, or due to the lack of maintenance of assets or areas associated with secondary functions (e.g. boat launching areas).	Changes to operational regime of dam (e.g. increase frequency of water level changes) or loss of secondary functions will need to be included within reservoir assessment.	1, 2: Risk to function (fishing or recreation) due to changes in water quality, quantity and temperature. 3: Stone pitching does not cover newly exposed water line following changes in operation. 5: Environmental drivers conflict with needs for form and function. 7: Rapid drawdown causing slumping and increase in pressure.
	Water quality issues leading to reductions in operation flexibility.	Changes in temperature, concentration (low flows) or storm runoff leading to water quality problems that affect function.	Consider links between form and function at design/planning stages to ensure sufficient resilience within the system.	2: Dam acts as a trout fishery and is vulnerable to water quality and temperature. 6: Water quality issues leading to reduced operational flexibility (exposure to peat, turbidity increases etc).
Monitoring and management	Implementation of adaptation measures may be more difficult for dams and reservoirs with more complex management arrangements.	Issues in identifying vulnerabilities and subsequent adaptation measures due to many stakeholders and opposing needs for form and function.	Needs to be allowed for when considering coordination and adaptation.	3, 7, 8-10,11
	Availability and use of trend data.	Periodical review of instrumentation is often not carried out over sufficiently long periods to gain longer term understanding of impacts.	Consider how trends can be readily gathered and monitored within existing management regimes.	General
	Stakeholder participation in surveillance and maintenance. Catchments and long embankments may inherently rely on multiple stakeholders for surveillance and management.	Loss of stakeholders that are familiar with the reservoir and catchment e.g. interior of flood detention reservoirs flooding too often to be viable for farming.	Consider the implications of impacts on function that may affect the viability of stakeholder businesses (land use, recreation etc).	5, 9, 11

6. Guidance and recommendations

This section provides guidance and recommendations which has resulted from the reviews, generic assessments and case studies. Guidance and recommendations are categorised according to lifecycle planning of a reservoir and are separated into the following sections:

- **Policy, planning and assessment**: issues that need to be considered when planning for a new reservoir and potential amendments to legislation,
- **Design and construction:** implications of climate change design standards,
- **Operation and maintenance**: flow charts and guidance notes on vulnerability assessments, monitoring and adaptation measures for existing reservoirs.

The most detailed guidance is provided within the operation and maintenance section (**Section 6.3)**, as this contains notes on the evaluation of both form and function that are applicable to the other sections.

6.1 Policy, planning and assessment

Policy, planning and assessment adaptation measures are mainly related to function. Relevant issues include regulations and planning required to address water demand, planning regulations required to facilitate modifications of existing dams and environmental regulations relating to operational adaptation. Some aspects of form can be affected, generally in response to policies or planning regulations, which can affect the sustainability and resilience of dams to climate change. This section summaries some of the key points identified during the project.

6.1.1 Policy

The areas of policy response that could assist in the adaptation of current and future dams to climate change are described below. These concentrate on the higher risk issues for form and function, as identified through the vulnerability assessment and the case studies. Potential policy responses include:

- The FWMA 2010 requires a risk based approach but as yet it offers no details as to how this should be achieved. Non-published draft guidance indicates that approaches based on the existing statutory arrangements are likely to be suitable, and this is reflected in the approach recommended within this report. However, the reservoir sections of the 2010 Act are dependent upon on the development of secondary legislation (regulations, statutory instruments and orders) so it is likely that many of the provisions in the Act will not come into force for some time yet. When this secondary legislation is drafted, it is recommended that risk based assessment should make specific reference to climate change in a way that links to the existing statutory arrangements, as demonstrated within this guidance.
- The majority of dam functions were found to be vulnerable to drier summers leading to lower water levels in reservoirs. Policy and regulation responses that aim to reduce demand are therefore helpful and important for reservoirs that are used for the seasonal storage of water. Such initiatives are already being promoted by both Ofwat and the Environment Agency. Similarly, the assessment of flood return periods and flood severity shows that climate change is likely to significantly increase the stress that is placed on existing flood storage reservoirs. Policy measures are already being promoted to reduce this through policies such as Planning Policy Statement 25 (Development and Flood Risk) and Catchment Flood Management Planning guidance. This includes the maintenance or reconnection of floodplains and the promotion of sustainable drainage systems to reduce urban runoff from new developments.
- Potential poor water quality and availability of compensation flows during dry summers was also a recurring theme in the workshops and case studies. Climate change needs to be considered when policies relating to licensing, compensation flows and discharge consents are being reviewed. This should include consideration of how prioritisation of water uses at times of climatic stress is controlled and implemented. Timescales involved in the implementation of drought response measures are particularly important as climate change can affect the nature of drought and demand, and hence the speeds at which reservoirs are likely to empty. Any reviews of the processes and legislation that surround drought response measures at reservoirs (e.g. Drought Orders to curtail compensation releases) should consider the impact that the lead times involved in their application can have on the effectiveness of the measures.
- Current planning policies tend to limit the scope for extension and development of dams as a response to loss of effective yield or lack of flood retention capacity. The risk that dam assets will need change their function or be abandoned as a result of climate change will be larger if extensions and non-safety critical capital works at dams continue to be difficult to implement.

- This assessment has also found that the ‘green’ measures that are currently being designed into dams in order to improve their planning acceptability and environmental attributes often do not consider the implications of climate change (see next section). It is therefore recommended that policies and guidance should require that the sustainability of such designs in the face of climate change is considered alongside the ‘usual’ drivers such as biodiversity and landscape impacts.
- Catchment management has been identified as a key factor in the potential impact mechanisms and constraints on dams and reservoirs. The effects of climate change need to be considered when land use policies that might affect reservoir catchments are being developed. In particular, policies and initiatives that promote lower runoff erosion rates (e.g. lateral ploughing, maintenance of set aside and buffer strips), or provide advice on the adaptive capacity of various crop types, are important. It is therefore recommended that reservoir catchments are identified as a specific concern when land use policies and agricultural guidance is being developed by governmental organisations.

6.1.2 Planning and assessment

Planning and assessment of the existing dam and reservoir stock is effectively covered in **Section 6.3** below. The policies and procedures that are used for planning new dams and reservoirs are already well established for Water Undertakers and the Environment Agency, and storage requirements for other users (e.g. farms, fisheries, recreation etc.) are highly site and situation specific. Guidance on flows and yield is provided in **Section 3.2.** of this document. The procedures and modelling that are used for future balancing storage, yield and demand requirements do not need to be discussed further in this section. However, there are a number of issues that do need to be considered alongside the basic hydrological factors when future storage facilities are being planned. Key considerations include:

- Climate change needs to be considered as an integral part of the planning of new reservoirs for seasonal water supply and flood management. As well as yield and flood flows, evaluations need to consider how secondary functions might be affected by climate change, particularly where this might affect the primary function or subsequent design. This includes:
  - The sustainability of planned recreational or fisheries use given future changes in reservoir levels or poor water quality (both from drought or increased frequency of flood waters) – see **Section 3.2.2** for further guidance on potential impacts.
  - The sustainability of the management or ownership regime that is proposed for the catchment and secondary facilities or general policies on ‘green engineering’ measures that are proposed for future designs. Environmentally conscientious operation and design is encouraged, but planners should consider how climate change (e.g. reduced rainfall/runoff availability for marginal wetlands, changes in catchment vegetation) might affect planned engineering approaches or ownership structures. Dams and reservoirs have very long operational lives, and it cannot be assumed that current climatic conditions will remain, particularly for functions or attributes that require vegetation types or hydrology to remain stable.
  - Catchment land use (including forestry) and risks presented by climate change. Catchment issues and risk assessment are addressed in **Section 6.3.2.**
- The case studies identified sometimes conflicting and opposing needs relating to form and function, which are likely to be exacerbated as climatic variability increases. Where reservoirs are planned to provide a number of functions or are likely to rely on multiple stakeholders to maintain and operate the overall reservoir function, then the impact that climate change might

have on the dam needs to be considered holistically at the planning stage. Practical guidance on the types of impacts that can occur is provided in **Section 6.3.4**.

6.2 Design and construction

In general, the risks and likely changes that are likely to be required for design and construction in response to climate change are effectively covered in **Section 6.3**, with particular issues highlighted by the design considerations and risk factors described in the information panes. In most cases these can be just as easily applied to new design and construction as they are to existing design and construction.

6.2.1 Existing reservoirs

The information panes that are described for each of the failure mechanisms within **Section 6.3** contain guidance on the risk factors that may cause problems with reservoir design. If major works are planned at existing dams or reservoirs, then these should take account of the relevant risk factors described within those information panes The potential scope of remedial actions and design adaptations ranges from simpler measures such as patching of cracks and joints following heat waves, through to significant works involving the installation of additional toe drainage or re-facing of parts of the spillway or dam.

6.2.2 New reservoirs

In designing and building new reservoirs there is an opportunity to consider the potential impact mechanisms caused by climate change within the design. As can be expected, each reservoir will have a unique set of requirements and constraints and hence it is important to think laterally and consider potential combination mechanisms for each reservoir. Future design standards will need to reflect the issues relating to capacity and water quality and will also need to allow for changes in vegetation type (incorporating drought tolerant species) and greater flexibility in use. Adaptation of design standards may need to include:

- Increased need for hydraulic capacity and useable flow (to account for higher rainfall, additional silt and vegetation build up in reservoir).
- A review of vegetation type and soil cover specification on the embankments, crest and (if green engineering is used) spillways, with particular reference to resilience to hot weather, drought and sunlight exposure (this includes ‘extreme’ effects such as grass fires). The use of wildflower cover, grasscrete, swale type drainage or “wetland” dips on slopes needs to consider how reduced rainfall or increased heat may affect their future performance.
- Additional coverage of clay cores and clay materials to minimise desiccation risks.
- A review of the use of materials liable to heat and ultra violet (UV) damage such as high density polyethylene (HDPE), geotextiles and liners.
- Review of the use of materials and construction techniques that may be affected by increased temperatures. This includes expansion capability and fill for joints, grass cover specification and any liners.
- A review of catchment related issues (see **Section 6.3.2**). Greater consideration of the effect that changes in catchment erosion rates, vegetation type and health may have on drainage, monitoring and maintenance needs to be applied at the design stage. This includes potential effects of vegetation blockage on embankment drainage and accessibility and availability for visual inspections (particularly where vegetation may hide burrowing animal activity).
- Consideration of the appropriate use of concrete specification to suit projected local climatic conditions, in particular the impact of UV radiation and increased temperature. Consideration

of the types of concrete joints, aggregates and derived products used both during the construction and design life of the structure is particularly important. British Standards will continue to apply (e.g. BS8007 on the design of water retaining structures) although the design thresholds may need to be increased as appropriate. The American Concrete Institute (ACI) Guide can provide additional useful guidance for more extreme conditions (e.g. standard 305R - Guide to Hot Weather Concreting).

- Considerations of how climate change may affect environmental features, particularly if these form a key part of the acceptability of the design or if they are likely to restrict future adaptation or maintenance access.

Guidance on all of the relevant climate change factors that underpin these considerations is contained within **Section 3.2.2.**

6.3 Monitoring, operation and maintenance

For existing assets, it is recognised that most dam owners will already have monitoring and maintenance regimes in place, and that these will generally be separated according to form and function. Monitoring and maintenance of form is effectively controlled by the statutory inspection process. Most owners rely on inspections and maintenance under Section 10 and Section 12 of the Reservoirs Act 1975 to provide recommendations for surveillance and maintenance actions, which support the routine weekly/monthly visits that are facilitated by the owners. The approach detailed within this section incorporates that regime and links it to recommended guidance on how to review the impacts of climate change on function. The guidance described in this section includes:

1. **Section 6.3.1– overview of the assessment process**. This provides a summary of how the decision making regime and coordination of the evaluation and adaptation process is managed. It also provides a summary of the key processes involved in the evaluation and adaptation of form and function.
2. **Section 6.3.2 – evaluation of catchment vulnerability.** The impact of climatic variability on reservoir catchments can significantly affect both form and function, so the evaluation of catchment vulnerability is described in a stand-alone section.
3. **Section 6.3.3 – vulnerability assessment and adaptation responses for form**. This provides details of the procedure that is recommended for asset owners and panel engineers to ensure the safety and integrity of the asset.
4. **Section 6.3.4– vulnerability assessment and adaptation responses for function**. This provides details of the procedure that is recommended for asset owners and other stakeholders to manage the functioning of the reservoir.

6.3.1 Overview of the assessment process

An overview of the general assessment approach that is recommended for the dam owner is presented and summarised in **Figure 6.1**. The proposed method consists of the following steps:

1. **Identify and define the decision context**. The 'decision context' covers the overall operating and maintenance environment under which the climate change assessment will be carried out. This stage of the process needs to be instigated or led by the asset owner and should be done at a relatively high level. The process includes the following steps:
    - Appoint an overall 'owner' of the climate change assessment process. This does not have to be the asset owner if Service Level Agreements or similar institutional arrangements exist. However, because the asset owner retains ultimate responsibility for the safety of the dam, they will be ultimately responsible for the decisions made in relation to climate change adaptation.
    - Decide who will take the overall **coordination role** for the assessment. This person will be responsible for technically ensuring that form and function are reviewed. The coordination role is crucial to assist lateral thinking and coordination of findings amongst all stakeholders. It is likely that the Supervising Engineer should be appointed to this role as they have the necessary background knowledge and will be able to understand the wider implications of any recommendations to the overall safety and functioning of the dam and reservoir.
    - Complete a pro-forma of the contact details and roles of all reservoir stakeholders as indicated in **Table 6.1** below. Whilst this information will be generally known, it is useful to review and ensure it is up to date before carrying out the assessment (as it will show who all the stakeholders are and hence where information can be obtained).

2. **Consult with stakeholders and confirm assessment mechanism**. At this stage the practical requirements of the process are addressed. This covers questions such as how basic information will be obtained (records, workshops, interviews, etc.) and how findings should be presented. This should be governed by the pro-forma assessment of operation and maintenance as described above. Recommendations for the format of outputs are provided in **Sections 6.3.3 and 6.3.4.** Where appropriate, stakeholders should be consulted to determine how their inputs will be included in the process. A general review of catchment vulnerability should be carried out by the coordinator for input to the assessments of both form and function (see **Section 6.3.2**).
3. **Gather data/expert inputs and carry out assessment for form** – see **Section 6.3.3** for process and recommended outputs.
4. **Gather data/expert inputs and carry out assessment for function –** see **Section 6.3.4** for process and recommended outputs.
5. **Coordination**. At this stage, the coordinator should review any recommendations that have been made for adaptations to form or function in response to climate change and determine if there are any conflicts or synergies. There are linkages between the vulnerabilities and adaptation responses for form and function, so it is necessary to ensure that the process contains an overall review of the implications of climate change to the asset as a whole. This is captured through an overall coordination role and feedback processes. For example, if catchment changes are being recommended for water quality reasons (function), then does this have any implications for the generation of debris or runoff rates which might affect risks to spillways etc (form). **It should be noted that reviews of form and function do not have to be carried out simultaneously – coordination and feedback can be carried out as and when required.**
6. **Review/amend recommendations (if required) and incorporate into management systems**. This stage involves the communication of the recommendations from the review into the appropriate management systems. In the vast majority of cases this will be through existing systems or roles (e.g. operations manager, asset management units, estate managers etc). Maintenance/capital works may need to be incorporated into Portfolio Risk Assessments (PRAs), if these have been carried out. If conflicts or issues have been identified between form and function, then assessments will need to be reviewed, either at the time or during the next risk assessment.
7. **Determine/update frequency of review and check assessment mechanisms.** Unless the dam or reservoir is known to have significant existing issues that may be climate related, it is recommended that the first reviews of form and function are carried out at the next convenient opportunity – e.g. during a Section 10 assessment or during a water industry Business Plan review. Following the initial reviews, the timing of updates should be determined based on risk to form and potential impacts on function. Given the resilience inherent within dam systems, the following suggestions are made for review periods (these are similar to the typical review periods recommended by the Inspecting Engineer):

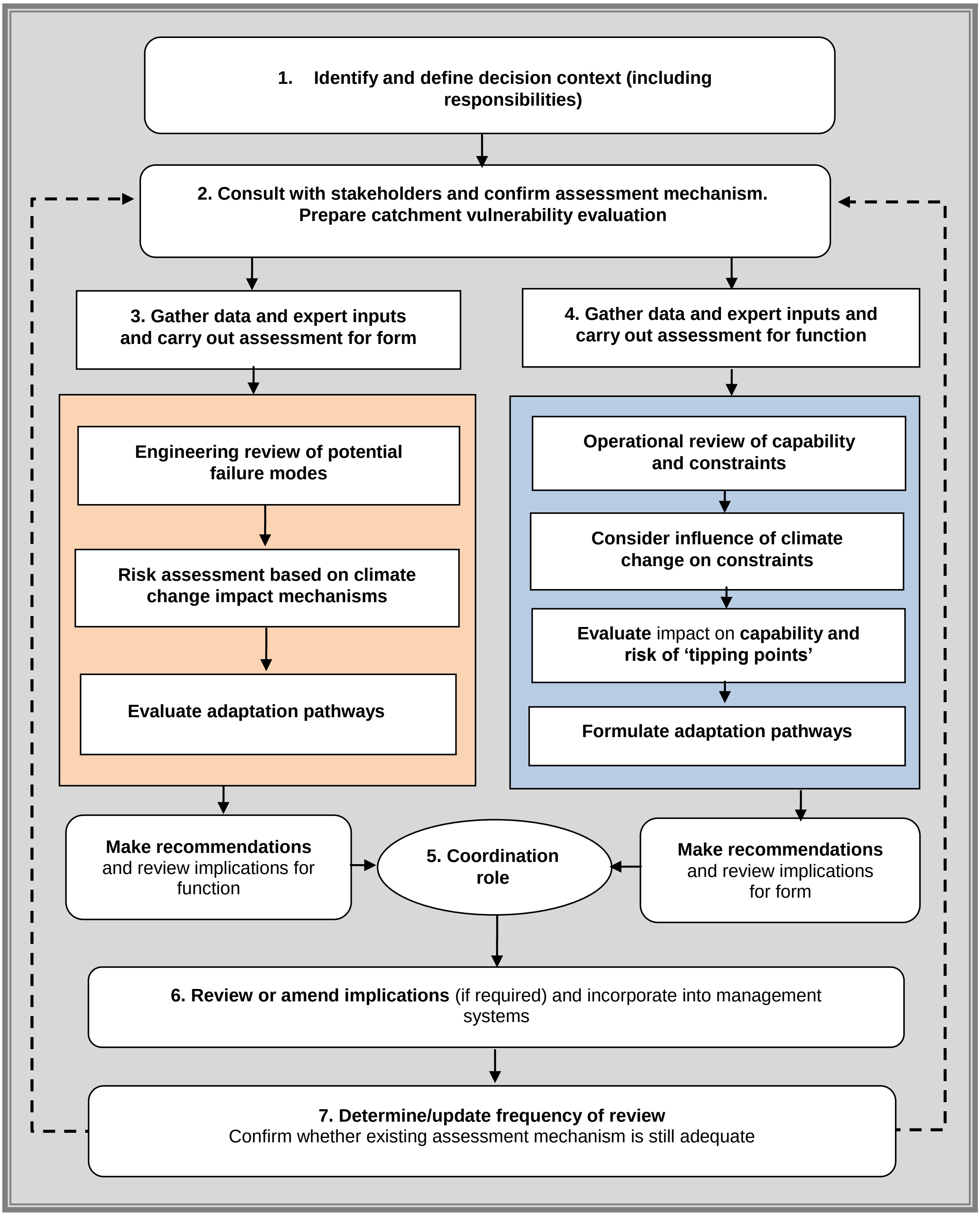
    - **High risk** (existing climate related issues that already present some risk to operation or safety; high vulnerability of function to small climatic variations) **5 years,**
    - **Medium Risk** (concerns that changes could lead to medium term operational or safety issues; potentially measurable impacts on function over the next 10 years) **10 years,**
    - **Low Risk** (some potential for impacts to form but unlikely in the medium term; possible minor impacts to function without near-term risk of 'tipping points') **20 years or upon major change of circumstances,**

- **Negligible Risk** (structures are not significantly affected by climate; very unlikely that function will be affected) **only review upon major change of circumstances.**

Table 6.1 - Information to update during the review of operations and management

Review item	Notes
Ownership	Who actually owns or leases the different parts of the dam structure, ancillary buildings, reservoir surrounds and catchment.
Surveillance and routine monitoring	How, and by whom, the Statutory inspection regime is procured and carried out.
Operation of dam and ancillaries - rules	What rules are there in place to govern the operation of the 'core' assets? This covers management of primary functions (control curves, releases, etc.) and any 'rule books' that govern the operations that are carried out to meet those functions. *Do not try to summarise actual control rules – simply refer to existing manuals or systems.*
Operation of dam and ancillaries - responsibilities	How the operation of the dam structure and associated ancillaries is carried out and divided between organisations (e.g. who operates the 'core' dam operations, who is responsible for operating ancillary assets such as hydropower etc).
Operation and management of catchment and 'secondary' functions	Who maintains forestry and farmland within the catchment (high level review), who manages functions that are not directly related to the dam's primary purpose (e.g. boating, fisheries, ecology etc).
Maintenance and capital works	How decisions and activities relating to reactive maintenance and new (capital) works are managed within the relevant organisation(s).

Figure 6.1 - Overview of the assessment process



See Section 6.3.3 for detailed methodology

See Section 6.3.4 for detailed methodology

6.3.2 Evaluation of catchment vulnerability

The risk that climate change poses to both form and function is heavily influenced by the nature of the catchment. Problems with the catchment represent a number of ‘risk factors’ for the evaluation of form and provide a number of key constraints for the evaluation of function.

This review should consider but not be limited to the following questions:

1. How close are trees to the reservoir, spillway or embankment? Are tall examples of vulnerable species present? Are trees vulnerable to storm/wind damage? Are live trees present in parts of the reservoir that only fill occasionally (usually only applies to flood detention reservoirs)?
2. If the catchment is steep and potentially prone to erosion, then is it vegetated with species which could be vulnerable to climate change? Upland bogs are likely to be most at risk, as changes can occur rapidly when they dry out. Wet vegetation on thin, sandy soils is also likely to be at risk from drought and subsequent more intense rainfall.
3. Are grassed parts of the catchment prone to waterlogging during wet winters? Can this cause large areas of bare land to develop when they dry out and subsequently increase silt transfer into the reservoir?
4. Does the rate of erosion depend heavily on catchment management measures? How might these change if climate change affects farming?
5. Are catch drains or catchwaters (i.e. man-made drains that transfer sub-catchment runoff within and between catchments) located in the catchment? Could these fail or block if the catchment degrades? What happens to the water then (e.g. could it be directed onto the dam mitre)?
6. Is the catchment prone to landslides? Could large slips occur if rainfall intensifies?
7. Do water quality problems exist within the reservoir as a result of catchment runoff? Could these change if land use or erosion rates change, as highlighted above?
8. Is the reservoir constructed on a groundwater dominated catchment[5]? Will the reservoir have sufficient capacity to accommodate groundwater-fed flows from the surrounding catchment area?

In most cases the answers to these questions will be obvious as any problems associated with climate change will represent a worsening of existing catchment issues. Potential exceptions include:

1. Climatic impacts on tree species. Key species that might be vulnerable to climate change are referred to in **Section 3.2 (Table 3.4**).
2. Potential drying of bogs is very difficult to predict and could occur in catchments with no existing problems. Where the catchment may be a concern, the most appropriate approach is likely to be to instigate a monitoring programme that examines how critical habitats are changing over time. This does not have to be intensive (e.g. review periods could be as little as every 5 years), but should be guided by an appropriately qualified ecologist. Monitoring may require collection and analysis of trends, e.g. shallow dipwell type piezometers can be used to provide trend data for groundwater levels in the peat.

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[5] Refer to Environment Agency Bulletin “on improving reservoir safety- Reservoir flood safety in ground water domintated catchments”. Available at http://publications.environment-agency.gov.uk/pdf/GEHO0808BPTV-e-e.pdf

6.3.3 Vulnerability assessment and adaptation responses: form

6.3.3.1 Evaluation Framework

The evaluation framework for form is shown in **Figure 6.2.** The process is designed to be carried out using a pro-forma such as that shown in **Figure 6.3.** This pro forma is compatible with the format and terminology as suggested in the Reservoirs Act 1975.

The evaluation framework uses **failure modes** and associated **impact mechanisms** rather than considering individual effects such as rainfall or temperature. This is because the case studies showed that climate change risks are often caused by a combination of effects that result in a specific risk to part of the asset. Detailed **'information panes'** are provided for each asset type and each failure mode in **Sections 6.3.3.2** to **6.3.3.5**.

When carrying out the evaluation, it is important that assessors think laterally and consider how the various risks and impact mechanisms might interact at the site. However, any scenarios that are considered should represent a feasible, significant combination of effects; it should be possible to discount most failure modes and impact mechanisms at an early stage. In most cases the feasible impact mechanisms will represent extensions of known problems that exist at the site or represent 'tipping points' that might occur if climate change exacerbates weaknesses or potentially problematic features.

Notes on the evaluation process are as follows:

1. **Engineering review of potential failure modes**. At this stage, the assessor should examine the design of each element of the asset and evaluate the 'risk factors' that exist for that element. The 'risk factors' refer to issues that might make the element vulnerable to climatic variations (e.g. poor mitre drainage design, thin topsoil cover or constraints on seasonal cutting). The best source of information on 'risk factors' is likely to be historic records, primarily the Statutory Inspection reports or the Supervising Engineer's statement and associated investigations, although other data sources may be available.

   The evaluation is initially carried out for each potential failure mode for each asset category in the following order:

   - Embankment,
   - Overflow structure (spillway),
   - Ancillaries.

2. **Vulnerability assessment based on impact mechanisms.** For those failure modes where the dam is vulnerable, the assessor should review the level of risk presented by the potential Impact Mechanisms.

   For erodible embankments, erosion failure modes are considered first, as erosion can serve to exacerbate the risk associated with failure modes such as piping or desiccation. These interactions are referred to as combination impacts and they form an important part of the evaluation process. Such combination impacts can also occur between asset categories (e.g. overwhelming of spillways leading to crest or face erosion). Further details about potential combination impacts are provided where applicable.

   They key points to consider when carrying out the vulnerability assessment include:

   - How the existing maintenance or management regime might influence the impact (e.g. is the site or asset remote or difficult to access).
   - How 'events' such as storms or drought may act to exacerbate or cause problems (e.g. heat stress on trees in the catchment may not be an issue until a storm event causes them to uproot and block the spillway).

- How time, both in terms of frequency/duration of events and the speed at which changes occur, affects potential loading of the embankment or operation of the spillway (e.g. drawdown rates might affect potential impacts such as increased settlement, damage to pitching, or damage to the spillway).
- If impact mechanisms could realistically and significantly increase the risk of failure or operational difficulties, then the assessor should evaluate the level of risk presented by the Impact Mechanism under climate change. **Risks should be considered based on a conventional approach, whereby *magnitude = likelihood * severity*.** Guidance on approaches that can be used to evaluate levels of impact is provided within the information panes. Because climate change varies with time and contains significant uncertainties, it is necessary to carry out a staged assessment process using the following guidelines:
  - Assessors should carry out an initial 'screening' process where they use longer term, higher climate change values and simpler assessment approaches to determine if the risk is 'plausible'. For effects that are directly related to rainfall or temperature, the 50th percentiles of the Medium Emission 2080 projections should be used as indicators. Where assessors need to consider low flows, then it is recommended that the 50th percentile for the 2050 High Emission Q95 data for the nearest river basin should be used (see **Table 3.2**), and be translated to the dam location using the maps shown in Error! Reference source not found.**.** For high flows and flood frequency, assessors should use the 2080 values referenced in **Section 3.2.2.3.** For impact mechanisms that involve changes in water levels in the reservoir or changes in how often and quickly those water levels fluctuate, then assessors can either use existing models or use the simple approach outlined in **Section 3.2.2.5** to give an indication of the degree of change that might be expected. The evaluation for other parameters (growing season, demand, etc.) should be based on the general values and approaches in **Table 3.4.**
  - If these values do not indicate that the risk is significant then the impact mechanism should generally be discounted, unless there is some uncertainty, in which case it should be noted as being 'feasible' but not currently a significant risk.
  - All other impacts are then considered to be 'plausible', some level of quantification of the risk should be carried out. For those measures that are directly related to temperature or rainfall, then the level of medium term risk should be reviewed using the 2050s, 50th percentile values from the 'plume plots' contained in **Appendix B**. Where necessary, impacts on flow rates, levels and reservoir fluctuations should be refined using the more advanced approaches indicated in **Sections 3.2.2.3** to **3.2.2.5.**

Guidance on the risk categories that should be used is provided in **Section 6.3.1**. Risks should be evaluated 'net' of the current operational and maintenance regime – i.e. is it feasible that problems could develop given the current operational and monitoring regime that is in place? Changes to monitoring or operation are part of the recommendations for adaptation and should be considered at the end of the assessment.

3. **Recommend adaptation pathways** Recommendations for changes to monitoring, operation or maintenance along with any remedial/capital works should be presented in the form of adaptation pathways. These are essentially a list of recommendations that form an overall 'plan' to adapt to the climate change impact. Further information is provided in **Section 6.3.3.6.** ***N.B. adaptation measures that involve changes to capital works or surveillance regimes must be checked with the Inspecting Engineer before they are implemented.***

Figure 6.2 - Evaluation framework for form

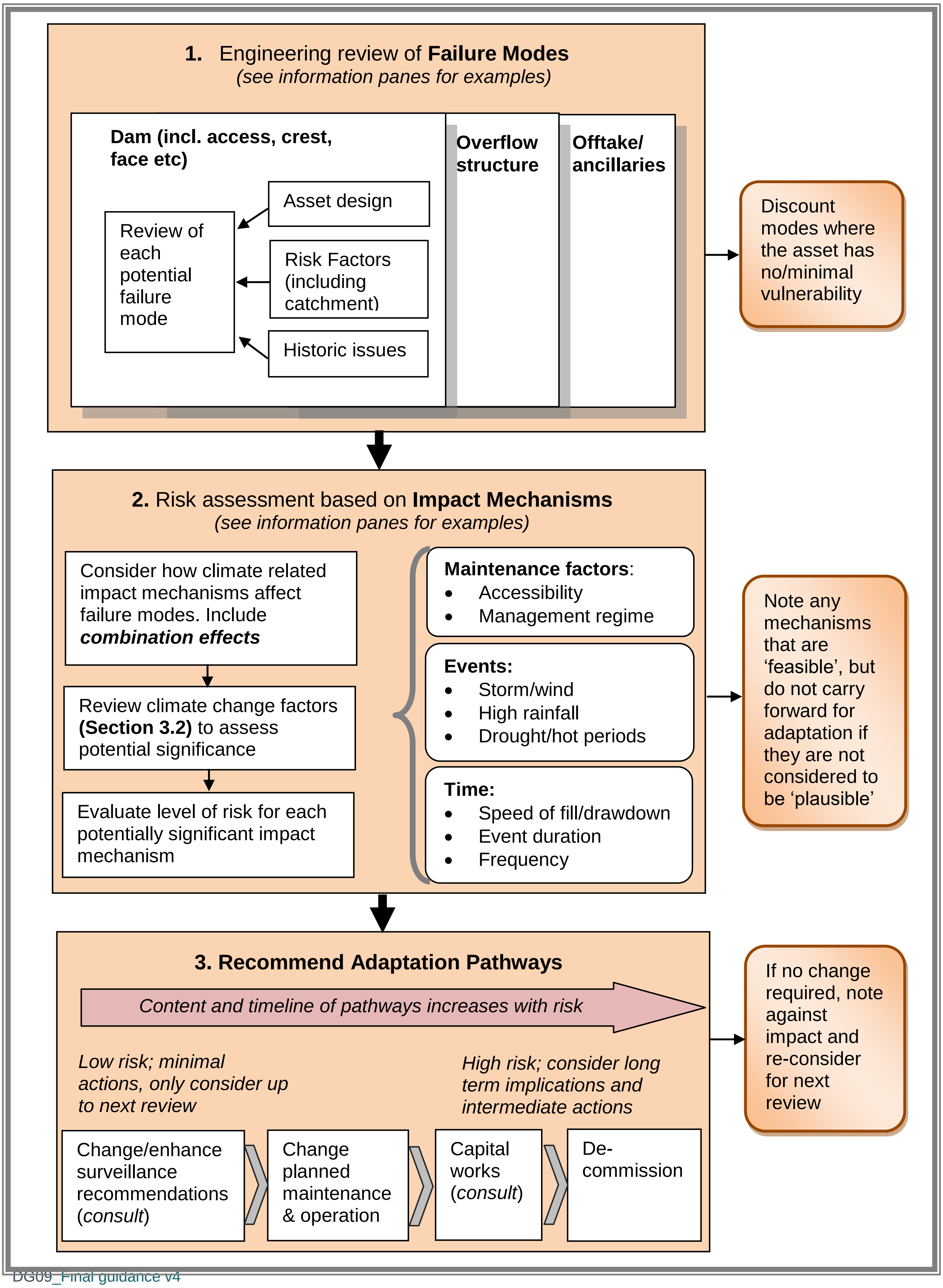

Figure 6.3 - Example pro forma assessment (erodible dams)

GENERAL NOTES	*Comments about management context etc. as appropriate*		
CATCHMENT ASSESSMENT	*Highlight any significant catchment risks, as detailed in Section 6.3.2*		
CLIMATE CHANGE RISK ASSESSMENT			
Impact Mechanism	*Significant? (Y/N)*	*Climate Change Risk (H, M, L, F*)*	*Notes and comments (**including Combination Impacts**)*
Dam			
Erosion of upstream face/shoulders			
Erosion of crest/ downstream face			
Piping or slumping			
Desiccation of core/blanket			
Failure/damage to clay or membrane liners			
Overflow structures			
Overwhelming/blocking of structure			
Damage or scour of spillway/stilling basin			
Ancillaries			
Damage to tunnels, valves or draw off facilities			
Expansion/seizure of metal components or electronic failure			
Other			
RECOMMENDATIONS FOR ADAPTATION MEASURES			
Monitoring	*Note any possible changes to the monitoring/surveillance regime required as a result of climate change risks*		
Maintenance	*Focus on preventative maintenance measures*		
Operation	*Indicate possible operational adaptations if impacts start to affect safety or require excessive maintenance*		
Capital works/other	*Include any further investigations/studies required to evaluate the need for works prior to the next review*		
RECOMMENDED REVIEW INTERVAL	*5, 10, 20 years or major change of circumstances only*		

*Risk level ‘F’ refers to it being feasible due to climate change uncertainty, but it is generally thought that it is unlikely to be significant in the medium term.

6.3.3.2 Specific guidance erodible embankments

Embankments made of erodible fill materials (homogeneous earthfill, clay core, lined earthfill) may, in some cases, be vulnerable to climate change as the drainage, fill material and cover have been constructed and are historically adapted to the 20th century UK climate. There are a number of impact mechanisms that can affect erodible dams as described below.

EROSION OF UPSTREAM FACE OR SHOULDERS

Design considerations

Pitching/face protection & beaching

Wave wall

Fetch

Shoulder drainage and material

Structures

Catchment & drainage lines

Risk factors

Nature of contact between pitching/face protection and beaching*

Vulnerable jointing on pitching*

Sheet piles on embankments*

Long fetch when liner or beaching exposed

Erosion prone catchment**

Trees/vegetation on embankment

Maintenance factors

Accessibility of pitching/face protection

Potential impact mechanisms

Prolonged low/fluctuating water levels leading to wave erosion on bottom of pitching or exposed shoulder areas, particularly where a long fetch is present

Prolonged low water levels leading to exposure and wave/sun damage to joint materials

Low water levels and intense rainfall causing erosion between face and shoulders

Fluctuating water levels or heavy rainfall causing drainage and erosion of joint materials*

Relevant climate change guidance

Low/fluctuating water levels – use guidance on yield (**Section 3.2.2.5)**

Rainfall intensity – use wettest day of the season (**Section 3.2.2.2, Appendix A)**

Notes

**Old materials can be vulnerable to rainfall or fluctuating water levels and some bitumens or polysulphides may be prone to heat/sun damage when exposed. Effects can be exacerbated by heavy rainfall and trees/shrubs growing in joints*

*** Erosion prone catchments, particularly in upland areas present a risk that catchment drainage lines or drainage lines may alter following erosion or landslips, which direct additional runoff onto mitre drains*

**** Refer to Environment Agency Bulletin " on improving reservoir safety-"Overtopping of embankments raised with sheet piles". Available to view at http://publications.environment-agency.gov.uk/pdf/GEHO0808BPTU-e-e.pdf*

EROSION OF CREST/DOWNSTREAM FACE

Design considerations

Drainage

Slope length/gradient

Face material (fill)

Grass cover

Access

Structures

Catchment & drainage lines

Nature/capacity of spillway & catchment*

Risk factors

Poor crest/mitre/face drainage.

Thin topsoil/poor grass mixes**

Exposed/south oriented face

Accessible by livestock***

Concentration of drainage/livestock erosion around structures or access roads***

Trees or shrubs on crest/face

Risk of downstream flooding

Burrowing animals

Erosion prone catchment****

Sheet piles on embankments*****

Maintenance factors

Grass cut – constraints or poor practice (includes blocking/grass kill caused by heavy cuts)**

Difficult access for monitoring/maintenance

Vegetation cover making detection/control of burrowing animals difficult

Potential impact mechanisms

Dry/hot periods leading to grass kill (frequency and duration) or increased winter rainfall leading to saturation and localised grass kill.

Warming leading to tree disease/stress in some species (followed by tree fall and uprooting)

Increase in growing season leading to increased growth in ground covering shrubs (reduces maintenance access, causes difficulties in pest control)

Increased frequency and duration of heavy rainfall on exposed areas or poor drainage

Relevant climate change guidance

Summer temperature – see changes in mean and hottest day (**Section 3.2.2.1 & Appendix A)**

Disease/tree stress and growing season – see **Section 3.2.2.6**

Rainfall intensity – use wettest day of the season (**Section 3.2.2.2, Appendix A)**

Flooding/high flows – see **Section 3.2.2.4**

Notes

**Overwhelming of spillway and resulting crest overtopping are covered in Section 6.3.3.4*.

Mixes used for environmental reasons (e.g. wildflower meadow) may be vulnerable and grass cutting period may be limited.

****Vehicle and livestock damage can be exacerbated if crest/road drainage is poor and cycles of waterlogging followed by drying out occur.*

**** *Erosion prone catchments, particularly in upland areas present a risk that catchment drainage lines or drainage lines may alter following erosion or landslips, which direct additional runoff onto mitre drains*

******Refer to Environment Agency Bulletin "on improving reservoir safety-"Overtopping of embankments raised with sheet piles". Available to view at http://publications.environment-agency.gov.uk/pdf/GEHO0808BPTU-e-e.pdf*

PIPING, SLUMPING OR SETTLEMENT OF EMBANKMENT

Design considerations

Fill material

Embankment dimensions**

Under drainage/filter drains

Structures

*Nature/capacity of spillway & catchment****

Risk factors

Uncompacted fill***

Ditches/preferential flow paths at toe of embankment

Existing 'wet spots'

Trees on embankment face

Burrowing animals

Flow concentration around erosion features***

Maintenance factors

Difficult access for monitoring/maintenance

Vegetation cover making detection/control of burrowing animals difficult

Spillway maintenance

Potential impact mechanisms

Rapid drawdown leading to slumping of upstream face (risk increased if water is held at high levels for long periods to improve yield prior to drawdown)

Prolonged/frequent fill of usually empty/low reservoirs leading to piping/core failure*** (*increased risk if blocking/overwhelming of spillway leads to loading in excess of design****)

Increases in size and frequency of water level fluctuation leading to piping or slumping

Heat stress/disease on certain tree species causing uprooting during storm events

Larger, more rapid fluctuations causing increased settlement rates within the embankment

Relevant climate change guidance

Low/fluctuating water levels – use guidance on yield (**Section 3.2.2.5)**

Increased flooding/filling of flood retention reservoirs – see **Section 3.2.2.4**

Disease/tree stress and growing season – see **Section 3.2.2.6**

Notes

*****Overwhelming of spillway and resulting overloading are covered in Section 6.3.3.4**.*

***Over-wide embankments are unlikely to be prone unless very poorly constructed.*

*****Piping risks are only likely around structures**, particularly where erosion or burrowing animals cause flow concentrations, **or in 'informal' embankments** where homogeneous silt clays have been used as the fill material.*

*****See later for combination effects.*

DESICCATION OF CLAY CORE*/BLANKETS

Design considerations

Core dimensions

Blanket design**

Fill type & depth of cover

Grass cover

Crest protection (road/other)

Risk factors

Thin core, permeable fill

Clay blankets with poor cover

No/poor crest protection

Erosion of crest or topsoil protection***

Burrowing animals

Poor grass cover

Shallow depth of cover

Maintenance factors

Vegetation cover making detection/control of burrowing animals difficult

Potential impact mechanisms

Prolonged emptying of reservoir leading to desiccation*

Prolonged, hot summer conditions leading to die off of grass cover (or grass fires) and deep penetration of drying conditions into fill material**

Longer growing season increasing shrub coverage and allowing greater activity by burrowing animals

Relevant climate change guidance

Summer temperature – see changes in mean and hottest day (**Section 3.2.2.1 & Appendix A)**

Vegetation stress and growing season – see **Section 3.2.2.6**

Low/fluctuating water levels – use guidance on yield (**Section 3.2.2.5)**

Notes

****N.B. desiccation of clay cores is not necessarily problematic if slow refill and close monitoring is used after desiccation has occurred – this can be reviewed with the Inspecting Engineer if a potential issue is identified.***

***Some embankments incorporate clay blankets on the upstream face rather than clay cores. These are particularly vulnerable if poorly covered when reservoir levels fall.*

****Loss of cover is generally dictated by the risk factors and events described under crest/face erosion. See later for combination effects.*

FAILURE OF/DAMAGE TO LINERS (IF PRESENT)

Design considerations

Type of liner

Weight/cover on liner

Fetch

Degree of exposure

Nature of join/joint with unlined areas

Risk factors

Age

No/poor cover

Poorly loaded HDPE* (farm reservoirs)

Potential for gaps or water penetration at tops or sides

Trees/shrubs near liner

Poor drainage causing rainfall/runoff down liner face

Maintenance factors

Accessibility to liner

Visibility for monitoring

Potential impact mechanisms

More frequent, prolonged emptying of reservoir leading to wind lifting and damage to HDPE liners*

More frequent, prolonged emptying of reservoir during summer leading to UV damage (all materials) or drying out and block cracking of asphaltic liners or clay liners

Heavy rainfall/erosion leading to increased runoff around liner edges/running water behind liner**

Heat stress damage or increased winter rainfall/saturation leading to trees falling onto the liner; increased growing season causing problems with shrub growth in jointing materials.

Relevant climate change guidance

Low/fluctuating water levels – use guidance on yield (**Section 3.2.2.5)**

Rainfall intensity – use wettest day of the season (**Section 3.2.2.2, Appendix A)**

Disease/tree stress– see **Section 3.2.2.6**

Notes

**This can be a relatively common problem. Wind speeds are not predicted to be affected by climate change, but climate change is likely to affect demand (human use or irrigation) and availability of raw water. Note combination impacts where erosion of face results in loss of cover and exposure.*

*** This is more likely when associated with damage/erosion of crest cover and crest drainage. See combination impacts below.*

Note on combination impacts for erodible embankments

Erodible embankments are potentially vulnerable to effects that combine erosion of the structure or catchment with instability, piping (particularly around structures) desiccation and damage to liners. The key risks are:

- Erosion near the toe of the embankment or around structures such as tunnels or penstocks can promote preferential drainage pathways through the embankment, which can promote piping. Erosion within the catchment can cause sedimentation or minor landslips, which can block drain outlets. Erosion of the downstream face could block mitre drains and toe filter drains which could lead to instability or, in extreme cases, piping failure.
- Erosion of the crest or face can result in damage to the protective crest cover (particularly where the crest is covered by an unsealed road, which can be damaged by cycles of wet winter conditions and dry summers) or loss of grass and topsoil cover. This can allow desiccation cracking to penetrate deep into the underlying fill material. Erosion around the sides of structures may exacerbate the risk as this can be deeper and more difficult to remediate.
- Erosion of the crest of face can result in drainage problems and loss of cover that expose liners to climatic damage.

When evaluating the risk to the embankment, assessors should therefore carry out an assessment of the erosion risk first and then use this to inform the evaluation of the level of risk that climate change presents to instability, slumping, piping or desiccation of the embankment, or failure of any liners that are present.

6.3.3.3 Specific guidance on impacts: non-erodible embankments

Embankments made of non-erodible materials (masonry, concrete, cyclopean masonry) tend to be very resilient. In most cases they will only be at risk where the design is known to be problematic or where materials are already flawed (e.g. significant cracks in concrete structures) or are showing signs of wear or age. It should be noted that embankments where masonry or concrete walls are incorporated into earthfill structures should be regarded as 'erodible' and the masonry is considered to be a 'structure' within that embankment for the purposes of the assessment.

Assessment notes on key impact mechanisms are provided below. The only combination impacts that need to be considered relate to the risk that spillway capacity might be exceeded (which could increase water height and hence loading on the embankment).

CRACKING, SPALLING OR JOINT FAILURE ON DAM FACE/STRUCTURE

Design considerations

Orientation

Known FoS

Size and type of joints

Risk factors

Large, south facing structure

Rapid loading and unloading

Older, exposed jointing; particularly where joints are undersized/blocked

Jointing materials*

Known cracks and movement

Drains/under-drainage

Maintenance factors

Accessibility for monitoring of movement

Potential impact mechanisms

Increased rate and frequency of loading/unloading associated with changes in level operation (yield or demand)

Very large diurnal fluctuation in temperature during summer heatwaves**

Low water levels leading to prolonged exposure of jointing materials to heat and UV

Increased expansion leading to spalling on older structures where joints do not allow sufficient movement ; specific risk around bridge structures

Relevant climate change guidance

Low/fluctuating water levels – use guidance on yield (**Section 3.2.2.5)**

Summer temperature – see changes in mean and hottest day (**Section 3.2.2.1 & Appendix A)**

Notes

** Polysulphides, bitumens; vulnerability to UV and high temperature needs to be considered.*

***The risk that this represents needs to be offset against the prediction that very cold winter periods, (which are generally more damaging) will tend to reduce in frequency and duration. Risks are only likely where temperature variations are accompanied by reduced thermal inertia due to reservoir levels being low in summer.*

OVERTURNING, SLIDING OR FOUNDATION FAILURE*

Design considerations

Factor of safety of dam during flood water levels

Nature of tie in between embankment and rock foundations

*Nature/capacity of spillway & catchment***

Risk factors

Low factor of safety during high water levels

Known leaks or foundation weaknesses

*Nature of spillway/crest overtopping design***

Maintenance factors

Accessibility for monitoring of movement

Potential impact mechanisms

Increased flood height (including increases caused by blocking of spillway) leading to overtopping/sliding**

Increased fluctuation in loading/unloading resulting in structural weakening prior to flood event

Relevant climate change guidance

Low/fluctuating water levels – use guidance on yield (**Section 3.2.2.5)**

Increased flood flow rates – see **Section 3.2.2.4**

Notes

** Overall, this impact has been included for completeness, but it is unlikely to be a significant risk unless there are known issues at the dam. It may increase monitoring requirements.*

Actual hydrological impacts are not predicted for PMF, so category 'A' dams do not need to be evaluated for increased loading during storm events, unless there is a risk that spillways might be blocked by catchment debris. This is covered in **Section 6.3.3.4

6.3.3.4 Specific guidance on impacts: overflow structures

Excedance of spillway capacity is one of the more ‘obvious’ risks from climate change, but it should be noted that currently this will only need to be checked for non category ‘A’ dams, which are designed to pass the PMF. There are no reliable predictions as to how the PMF might be affected by climate change, however allowing for the PMF is a very stringent standard and it is unlikely that the overall level of risk will change significantly in relation to the experimental error that already exists within the calculations.

As well as direct hydrological changes, the risks of heat damage, erosion, sedimentation and blockage need to be considered when carrying out the assessment. Evaluation of catchment risks is therefore particularly important for this stage of the assessment. Assessment notes on key impact mechanisms are provided below.

CREST OVERTOPPING FOLLOWING EXCEEDANCE OF OVERFLOW CAPACITY (INCL BLOCKAGE/SILTATION)

Design considerations

Design capacity

Dimensions

Nature of catchment

Nature of spillway approach

Debris screens/protection measures

Risk factors

Shallow approach*

Catchment that is prone to landslip/erosion

Catchment containing vulnerable trees/large vegetation**

Spillway dimensions or intake screens that are prone to blockage

Maintenance factors

Difficult to clear screens/spillway during storm conditions

Accessibility of spillway approaches for dredging/clearance

Potential impact mechanisms

Increased rainfall leading to higher storm runoff; consider in combination with:

- Increased rainfall intensity or drying out of catchment resulting in sediment build-up around spillway or landslides during storm events*
- Heat/drought stress or increased winter saturation leading to damage of vulnerable trees within the catchment, causing uprooting and subsequent spillway blockage during storm events.
- Increased frequency of stored floodwaters damaging health of trees in flood reservoir footprint; leads to uprooting and potential for spillway blockage during the storm event

Relevant climate change guidance

Increased flood flow rates and frequency of flood retention – see **Section 3.2.2.4**

Rainfall intensity – use wettest day of the season (**Section 3.2.2.2, Appendix A)**

Disease/tree stress– see **Section 3.2.2.6**

Low rainfall drying catchment or winter rainfall water-logging – use rainfall changes (**Section 3.2.2.2**, **Appendix A)**

Notes

** Shallow approaches to spillways are potentially problematic for a number of reasons. Sediment buildup and increased risk of blockage is one, but there may be a risk of 'beaches' forming near the spillway, allowing shrubs etc to grow that could cause blockage during design storms*

*** As identified in the catchment assessment*

**** Refer to Environment Agency Bulletin on improving reservoir safety-"Vulnerability of Masonry Spillways". Available to view at http://publications.environment-agency.gov.uk/pdf/GEHO0808BPTW-e-e.pdf*

DAMAGE OR SCOUR OF SPILLWAY/STILLING BASIN (Includes excess flow rates)

Design considerations*

Hydraulic design

Material (including mortar/jointing)

Coverage of engineered surfaces

Nature of natural slopes

Nature of receiving water course

Risk factors*

Erodible bank materials around the engineered sections

Runoff/drainage around engineered sections

Exposed jointing**

Masonry Spillways*

Thin grass cover on 'green' reinforced grass type spillways***

Vegetation growth on jointing or side walls

Maintenance factors

Accessibility of spillway banks/sides

Coverage of banks or engineered surfaces by shrubs/bushes

Potential impact mechanisms

High summer temperatures/diurnal variation leading to expansion cracking of concrete spillways****

Increased rainfall intensity leading to increased frequency, height and velocity of spillway operation:

- More rapid deterioration of flaws in the spillway or erosion of unprotected areas***, exacerbated by possible trees etc in flows from catchment degradation
- Out of channel flow scouring banks/reinforced bunds around spillway channels

More intense wetting/drying cycles and rainfall leading to erosion of natural banks or erosion/infiltration around engineered sections.

Longer growing season leading to more rapid and extensive vegetation encroachment onto walls or structures

Relevant climate change guidance

Summer temperature – see changes in mean and hottest day (**Section 3.2.2.1 & Appendix A)**

Increased flood flow rates and frequency of flood retention – see **Section 3.2.2.4**

Catchment disease/tree stress– see **Section 3.2.2.6**

Low rainfall drying catchment – use summer rainfall changes (**Section 3.2.2.2**, **Appendix A)**

Vegetation growing season – see **Section 3.2.2.6**

Notes

*** Following the 2007 incidents, significant research has been carried out into the risk of high flow rates on masonry structures. The Environment Agency has published a bulletin on this issue -"Vulnerability of Masonry Spillways" which is available to view at http://publications.environment-agency.gov.uk/pdf/GEHO0808BPTW-e-e.pdf*

*** Exposure of vulnerable materials to UV damage or large temperature fluctuations*

****Thin grass cover over reinforced grass type spillways can be a concern as this could be prone to drying and grass kill – this can change the hydraulics during a spill event and increase the vulnerability of the reinforced grass 'system'.*

***** Needs to be offset against the prediction that very cold winter periods, (which are generally more damaging) will tend to reduce in frequency and duration. Only a risk where orientation and exposure tends to lead to very hot conditions around the spillway*

Specific guidance on impacts: ancillaries

Ancillaries include draw off towers, tunnels, valves, pipework, hydropower installations and even assets such as primary treatment facilities. Because of the wide variety in type, design and construction, it is not possible to be as prescriptive about this asset class. Some outline, generic information panes for some of the potential mechanisms are provided below, but these are unlikely to be comprehensive. Any assessment should consider ‘other’ risks, as determined by the engineer.

DAMAGE TO TUNNELS, VALVES OR DRAW OFF FACILITIES

Design considerations

Highly variable

Risk factors

Catchment containing vulnerable trees/large vegetation

Tunnel drainage/infiltration issues

Erosion prone catchment or structures located in erosion prone areas

Structures at risk of flooding*

Structures in areas subject to long fetch or high velocities during flood events

Shallow/silt prone areas around inlets to valve structures

Maintenance factors

Highly variable

Potential impact mechanisms

Increased rainfall intensity or drying out of catchment resulting in erosion and/or sediment build-up around ancillary structures or landslides during storm events*

Heat/drought stress leading to damage of vulnerable trees/other vegetation within the catchment, causing uprooting and increased debris in the reservoir. May damage offtakes etc through blockage or in combination with wave movement.

Increased frequency of stored floodwaters damaging health of trees in flood reservoir footprint; leads to increased debris in the catchment as above.

Higher winter reservoir or ground water levels leading to increased infiltration rates to tunnels causing damage to valves and buildup of ochre/other deposits

Increased catchment sedimentation leading to silt buildup or blocking of inlets to valve structures

Shrinkage of embankment fill away from structures due to dessication; leading to potential piping**

Relevant climate change guidance

Rainfall intensity – use wettest day of the season (**Section 3.2.2.2, Appendix A)**

Catchment vegetation degradation & disease/tree stress– see **Section 3.2.2.6**

Low rainfall drying catchment – use summer rainfall changes (**Section 3.2.2.2**, **Appendix A)**

Increased flood flow rates and frequency of flood retention – see **Section 3.2.2.4**

Impact on groundwater levels - see **Section 3.2.2.6**

Notes

** Either from overtopping or flooding of downstream water courses*

*** Particular in-combination effect – see previously for erodible embankments*

OTHER (Incl EXPANSION/SEIZURE OF METAL COMPONENTS OR ELECTRONIC FAILURES)

Design considerations

Location of pipework, valves etc

Nature of buildings, kiosks etc

Other - variable

Risk factors

Exposed components

Old/problematic valves or other moveable parts

Leaks/poor weather protection for component housing

Maintenance factors

Highly variable

Potential impact mechanisms

Increased winter rainfall leading to wet conditions and rusting of components; increased likelihood of electrical failure

Hot, prolonged summer conditions leading to expansion and metal fatigue in exposed pipework and valves

Other: e.g. algae or aquatic plant growth obscuring monitoring sites or gauge boards.

Relevant climate change guidance

Increased winter rainfall – use mean winter precipitation (**Section 3.2.2.2, Appendix A)**

Summer temperature – see changes in mean and hottest day (**Section 3.2.2.1 & Appendix A)**

Other – see previous guidance

Notes

None

6.3.3.6 Guidance on adaptation pathways for form

Consideration of adaptation measures involves a simple, three point process:

- Review the risk factors and the impact mechanisms involved,
- Evaluate the level of uncertainty and risk to determine what additional monitoring/surveillance is needed,
- Consider what the ultimate impact might be (i.e. what works may be required if nothing was changed) and determine how maintenance and operation might be changed to prevent the need for such works.

A summary of the typical 'generic' types of adaptation measures that might be required for the various asset components is provided in **Appendix E**. However, actual recommendations should be more specific and concentrate on the potential impact mechanism. They will be similar to the types of measures contained in the Section 10 Reports and Section 12 Statements, although the timescales and uncertainties involved in climate change means they will tend to concentrate on additional monitoring and possible operational changes or preventative changes to maintenance. Examples of 'realistic' adaptation responses are given in **Table 6.2** below. **It should be noted that in most cases adaptation measures will only include monitoring and maintenance measures; the table includes operation and remedial works in order to show complete examples.**

Where possible, assessors should consider and present adaptation measures in the form of a timeline. This should include indicators and triggers that can be used to determine when changes in maintenance might be required, how/why this may be no longer practicable and when changes in operation or even remedial works might be required.

Although surveillance and monitoring is already covered by the statutory process, modifications to the nature and timing of these visits may be required in response to climate change risks. General comments in relation to this are provided below:

- Inspection Engineers are required to state what types of records are recommend as part of a normal inspection regime. However, the consequences of climate change may impact new areas not previously considered as part of the inspection regime. For example, instruments may have traditionally been installed at the reservoir toe to measure settlement or pore water pressure. With prolonged periods of drying and wetting, the upstream catchment or faces of the reservoir may become more prone to settlement, heave or landslips.
- Under the Reservoirs Act 1975 the Engineers may state that inspections should be carried out during certain periods or following extreme climatic events. As part of climate change adaptation it would be advisable to ensure that this includes extreme events such as extended periods of drought or perhaps when reservoirs are operated close to their limits (e.g. when a water supply reservoir is operated at maximum drawdown).
- Although Inspecting and Supervising Engineers provide periodic guidance on monitoring and maintenance, Undertakers may need to take a more proactive role in inspecting the assets in order to ensure that the dams are monitored during periods of climatic stress.

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Table 6.2 - Indicative example of adaptation pathways

Asset type	Example impact mechanisms	Example adaptation pathways			
		Monitoring	*Maintenance*	*Operation*	*Capital works*
Erodible dam – upstream face	Erosion of areas exposed at low water.	Ensure site visit is carried out when levels are low to review wave erosion on key areas.	Increase frequency of pitching maintenance.	Amend control curve to avoid water levels staying at inappropriate levels for long periods.	Add rip-rap to vulnerable areas.
Erodible dam – downstream face	Loss of grass cover and high rainfall resulting in face erosion.	Monitor health of grass cover; note duration of bare patches following drought periods.	Alter mowing regime, sow drought resistant grass types. Increase frequency of drainage maintenance.		Increase topsoil cover and improve drainage if persistent problems are observed.
Erodible dam – fill and core	Slumping of upstream face.	Install piezometers on upstream face to monitor pressure changes during rapid drawdown.	Increase frequency of maintenance to drainage if risk identified.	Modify control curves if pore pressures indicate risk.	Install additional drainage if maintenance measures insufficient.
Erodible dam – liner	Lifting of HDPE liner following exposure and loss of cover.	Carry out supervising visits when water levels are very low.	Re-profiling/maintenance of cover during low water levels if cover deteriorates.	Change in usage if problems start to occur due to regular low water levels (e.g. change crop rotations to change irrigation use).	Additional weighting or cover added if maintenance becomes too onerous.
Non-erodible dam	Joint failure of face materials.	Enhanced monitoring of joint movement.	Joint filling or minor remedial works if movement starts to increase.	Possibly maintain higher water levels in summer (if realistic).	Chasing or filling of joints or cracks with 'modern' methods.
Overflow structure	Overwhelming of spillway due to catchment debris.	Regular monitoring of 'at risk' tree species in catchment.	Increased vegetation management measures (coppicing, tree removal).		Introduce booms or other protective measures.
Ancillaries	Damage or silting of scour valves.	Monitor catchment erosion and silt levels in reservoir.	More frequent dredging or debris removal.	Increased scour valve operation, introduce catchment management measures.	Introduce re-profiling or reservoir edge protection in key areas.

6.3.4 Vulnerability assessment and adaptation responses: function

The evaluation framework for function is shown in **Figure 6.4.** The process works by examining how the functioning of the asset can be constrained by climatic variation and then reviewing how climate change might alter conditions at the reservoir in relation to these **constraints**. It also considers how those effects might result in **'tipping points'** that could significantly compromise the current functioning of the dam.

As with form, **'information panes'** that give function specific details of the assessment process are provided in **Sections 6.3.4.1 to 6.3.4.6**. These contain examples of the climate related constraints that can exist for various functions and the degree of impact and 'tipping points' that might occur through climate change.

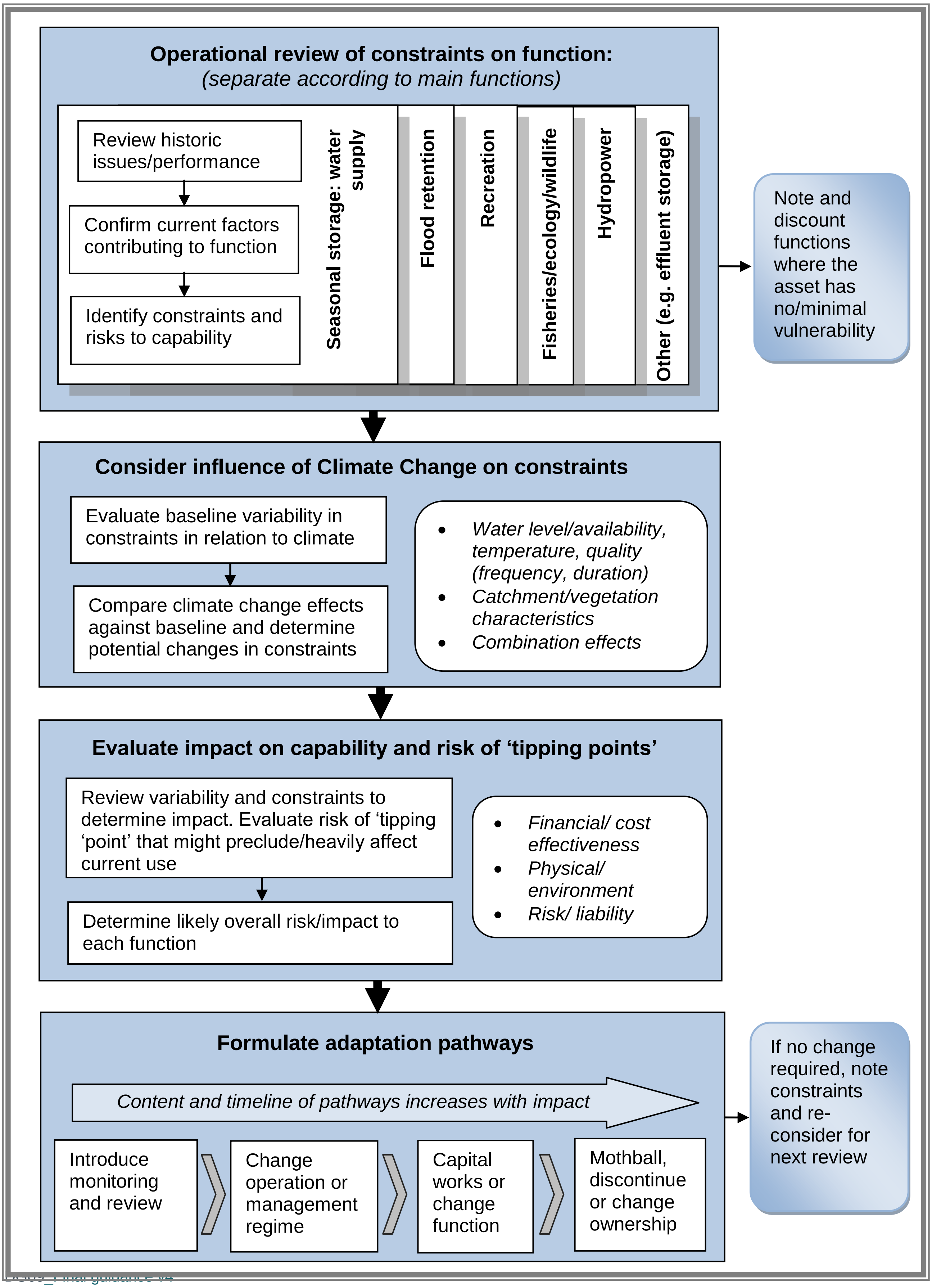
General notes on the stages of the evaluation process are as follows:

1. **Operational review of constraints on function.** Consider what physical parameters limit the current operation of the reservoir. This should cover all functions and consider 'obvious' constraints such as flows/yield as well as some of the less obvious constraints identified in the information panes. This process is based on a combination of historically recorded issues, liaison with stakeholders and logically considering the physical parameters that contribute to the functioning of the reservoir (e.g. for a fishery, enough water at the right quantity, quality and temperature is required – problems with these parameters can lead to constraints such as parasites or poor fish health, which can limit the catch season or type of fish).
2. **Consider influence of climate change on constraints.** Evaluate what sort of baseline fluctuation occurs in relation to climate. This includes many of the factors that are considered for form – i.e. yields/droughts, flooding height and frequency etc. It also includes parameters such as water temperature and water quality and the effect that the catchment can have on function. Any climate related issues that can affect operational assets that are needed to provide the required function (e.g. silting of internal penstocks, blockage of transfer pipelines) should also be considered.
3. **Evaluate impact on capability.** Comparing the level of baseline climatic variation against predicted climate change will give an indication of how conditions within the reservoir may change in relation to the known constraints. This can involve detailed predictive modelling (e.g. yield assessments for water supply reservoirs) however in most cases a semi-qualitative approach is likely to be applicable. The vulnerability of the particular function to climate change should be classified into one of the following categories:
    - **High** - climate change is potentially large in comparison to baseline variation and is likely to affect some constraints that are critical to the reservoir function (e.g. if climate change is likely to affect the severity of existing algal blooms and the current treatment capacity is struggling to cope with the blooms that already occur, then the vulnerability of the water supply function would be considered to be 'high').
    - **Medium** – climate change is significant in comparison to baseline variation and there is a reasonable medium term chance that it will significantly affect some of the constraints that are critical to the reservoir function.
    - **Low** – either climate change is small in comparison to baseline variation or climatic variation of this type is unlikely to significantly affect any of the constraints that are critical to the reservoir function.
4. For high and medium vulnerabilities the potential for **'tipping points'** should then be considered. For example, if droughts are already making sailing activities unpleasant and difficult (due to reservoir size, launching capability etc.) then the assessor should consider

whether there comes a point when the sailing club at the reservoir will no longer be viable. **If a 'tipping point' is identified, then the implications of this on the other reservoir functions, dam and catchment should be considered.** The purpose of identifying 'tipping points' is that it gives advanced warning of potential rapid changes in function or stakeholder involvement. A change in function or stakeholder involvement may affect the monitoring and maintenance regime that exists at the reservoir or within the catchment, and could have a knock on effect on other functions. Advanced warning is therefore required to allow adaptation measures to be implemented before this happens.

5. **Formulate adaptation pathways.** Adaptation pathways are likely to include changes to monitoring and surveillance within the catchment and reservoir, which may require that data are recorded so trends can be monitored in future reviews. Other adaptation measures include changes in operation (including changes to seasonal use patterns) and preventative maintenance. In some cases it may be necessary to change or remove some functions all together – in such cases 'early warning' based on monitoring is usually advisable to help plan for the implications of such changes. Further guidance is provided in **Section 6.3.4.7.**

Figure 6.4 - Evaluation framework for function



Specific guidance: seasonal storage for water supply

This generally relates to storage for potable use or irrigation, but can also represent any situation where water is taken from the reservoir and used for other purposes (e.g. cooling, off-site recreation).

Potential constraints

Yield: lack of rainfall leading to low inflows or availability of water for abstractors

Demand*:* increasing demand (human use or irrigation) leading to excessive pressure on water levels (possible conflicts with other functions)

Water quality - sedimentation/turbidity: increasing sediment inputs causing problems with treatment or use of transfer/abstraction equipment. Includes 'high colour' runoff from peat areas

Water quality - algae/vegetation: increased severity and duration of blooms causing treatment and operational problems

Water quality - other: decreases in dilution due to decreases in yield, or increases in pollutants due to catchment changes, leading to other water quality changes

Other – possible environmental constraints if water quality is no longer acceptable for compensation releases; this includes possible constraints on discharges caused by invasive species/pests

Approaches to evaluating climate change impacts

Yield (lower summer rainfall/higher temperature): see **Section 3.2.2.5**

Demand (higher temperature)*:* see guidance in **Table 3.4.** For irrigation consider absolute demand change, and increase in growing season.

Sedimentation/turbidity (higher rainfall intensity, higher temperature)*:* advanced approach is to gather data and review correlation with inflow/source water flow rates, then use indicators in **Section 3.2.2.5** to assess changes in flows. Simpler approaches are detailed in **Table 3.4**

Algae/vegetation (higher temperature)**:* see guidance in **Table 3.4**

Water quality; other (higher temperature, rainfall intensity): use changes in yield as above to determine concentration. Other relationships will be site and parameter specific (e.g. increases in point source and diffuse pollution in source water due to higher runoff rates in catchment)

Considerations for possible 'tipping points'

Yield/demand – points at which the reservoir can no longer meet demand**.** Specific approaches are used for the water industry (Water Resource Management Plans), but for farms etc. the owner will need to consider the financial implications of changes in the supply/demand balance.

Water quality – points at which current uses/treatment are no longer suitable or adequate*.* This could be 'absolute' – i.e. average water quality is no longer acceptable - or could represent the point at which seasonal/transient restrictions stop the reservoir from being viable for its current use.

Notes

**When considering algae risk, the current level of nutrients need to be considered as these may increase due to changes in runoff/land use.*

Specific guidance: flood retention

This includes washlands, impounding structures and other types of detention areas (e.g. 'levels'). 'Combination impacts' between recreational use, wildlife and catchment management (farming) are likely given the wide variety of types and other functions at these facilities.

Potential constraints

Flood volume*:* larger flood volumes resulting in inadequate protection of downstream areas by reservoir

Sediment & debris*: increased siltation/debris from catchment *(see* **Section 6.3.2.** *for details of mechanisms)* reducing capacity and affecting the functioning of the asset (e.g. through blockage of sluices/tunnels that are used to empty the reservoir between flood events).

Vegetation growth*:* increased growth of vegetation within the storage area. Possible minor reduction in storage capacity or interference with operation, as above.

Impact on land use within the facility*:* where facilities are farmed, then the impact of changes in the frequency of flooding on the viability of that farming will need to be considered, particularly as this could affect the management and maintenance regime around the reservoir.

Approaches to evaluating climate change impacts (see Section 3.2)

Flood volume (higher rainfall intensity): advanced approaches, use Flood Estimation Handbook (FEH) or other existing models combined with percentage changes in maximum daily rainfall (wettest day of the season). Simpler 'rules of thumb' are provided in **Section 3.2.2.4.**

Sediment & debris (higher rainfall intensity, other factors**)*:* assume sedimentation rates/problems increase in line with percentage increase in wettest day of the season, but modify for other risk factors as detailed in **Section 6.3.2.**

Vegetation growth (higher temperature)*:* difficult to quantify. Use increase in growing season **(Table 3.4)** as a guide to how much worse existing problems might become.

Considerations for possible 'tipping points'

Land ownership and use may represent a 'tipping point', particularly for large floodlands. Problems may start to occur if area is normally farmed and frequency of flooding makes this un-economic. This can result in a stepped change in surveillance and maintenance capacity for the asset.

Notes

** Key 'combination effect' with spillway and ancillaries. The issue over blockage/performance of flood detention facilities will need to be well coordinated between form and function.*

***Factors include drought/heat stress on catchment vegetation prior to storm events – see* **Section 3.2.2.6.**

Specific guidance: recreation

Recreation is often a secondary function, often involving different management from the primary function. Many of the impacts are therefore 'side effects' of the changes and impacts that occur on the primary function (normally flood retention or water supply). Recreation includes activities such as walking, canoeing and boating but excludes fishing, birdwatching and wildlife conservation, which are addressed separately.

Potential constraints

Low/fluctuating water levels*:* increases in demand or reduced yield leading to greater exposure of banks. Can reduce aesthetic value and make activities such as boating/sailing more difficult*

Water quality: lower water levels causing pollutant concentration. Warmer conditions leading to increased algal growth (including blue/green algae). Increased turbidity/sediment from catchment resulting in more stagnant conditions and poor aesthetics.

Vegetation growth*:* increased vegetation growth due to longer growing season causing navigation difficulties or problems with access to the reservoir

Increase in visitor numbers/season*:* increasing visitor numbers that might place a strain on the existing facilities (car parks etc)

Pests and malaria*:* increase in mosquitoes /biting insects with possible associated disease risk.

Approaches to evaluating climate change impacts (see Section 3.2)

Low/fluctuating water levels (lower summer rainfall, higher temperature*):* assume problems increase in line with reductions in yield. See **Section 3.2.2.5** for guidance on yield.

Water quality (various): See <u>*storage for water use*</u> for possible approaches.

Vegetation growth (higher temperature): difficult to quantify. Can use increase in growing season as a guide to how much worse existing problems might become (**Table 3.4)**.

Increase in visitor numbers/season (higher temperature, lower summer rainfall): low risk; use local data if evaluation is required

Pests and malaria (higher temperature): Can use increase in growing season as a guide to how much worse existing problems might become. Malaria is low risk, but other diseases such as West Nile virus may be a concern – see **Table 3.4.**

Considerations for possible 'tipping points'

The financial viability of clubs/lakeside businesses and visitor facilities is likely to be a key tipping point if conditions deteriorate at the reservoir. Liaison and 'early warning' over the extent of problems is advisable to ensure that the dam owner is aware of any risks that might threaten the viability of clubs or facilities.

Notes

** Depends on facilities at the reservoir – some may have launching areas that are designed to operate down to very low water levels.*

Specific guidance: fisheries, ecology, wildlife

Potential constraints

Water temperature*:* increases in water temperature leading to fish distress or unsuitable conditions for key macrophytes/macro-invertebrates (resulting in either direct ecological impacts or loss of food/prey species). Includes both peak temperature (leading to dissolved oxygen (DO) 'sags') and longer warm periods (which can increase problems with fish parasites etc).

Water quality - sedimentation/turbidity: increasing sediment inputs causing problems with turbidity. (includes 'high colour' runoff from peat areas). May create unsuitable conditions for existing species (includes DO 'sags' and siltation causing smothering of breeding gravels/food areas). Poorer visibility and appearance may deter fishermen or birdwatchers.

Water quality - algae/vegetation: as above, includes DO sags and poorer visibility/appearance.

Water quality - other: increase in pollution concentrations due to lower water levels in the reservoir or increased pollutant loads due to more intense rainfall causing additional contaminants to enter source waters from wastewater treatment works, farms etc.

Lower/fluctuating water levels: may prevent growth of marginal vegetation; leads to loss of food and cover for fisheries and birds. Can also create problems with access for bankside fishing.

Changes in marginal/catchment vegetation*:* changes in vegetation growing around the reservoir (or within the reservoir footprint for flow retention facilities) can affect bird populations and affect the availability of shading/refuge for fish and other aquatic species. May directly affect ecologically sensitive communities (e.g. Sites of Special Scientific Interest (SSSIs) designated for particular flora).

Approaches to evaluating climate change impacts (see Section 3.2)

Water temperature (higher temperatures, lower summer rainfall) – use change in summer maximum **(Section 3.2.2.1)** for absolute temperature changes. Use increase in growing season for change in duration of warmer conditions (**Table 3.4)**. Cooling inputs from catchment runoff may be important, in which case reductions in summer rainfall should be incorporated into the overall impact*

Water quality - sedimentation/turbidity: see *storage for water use* for possible approaches, but also allow for temperature effect on DO if risk is high (**see Table 3.4**)

Water quality - algae/vegetation: see *storage for water use* for possible approaches, but also allow for impacts on DO when algal blooms collapse if risk is high (**see Table 3.4**).

Water quality - other: see *storage for water use* for possible approaches

Lower/fluctuating water levels**:** see *storage for water use* for changes in yield. Assume littoral exposure increases in line with changes in yield.

Changes in marginal/catchment vegetation*:* see **Section 6.3.2** and **Table 3.4** for guidance on species vulnerability and changes in growing season.

Considerations for possible 'tipping points'

Financial viability of fisheries. Although adaptations such as changing from trout to coarse fisheries are possible, the commercial implications of such changes may need to be considered.

Notes

** This can be difficult but a 'rule of thumb' is that this is only significant for fairly small reservoirs. Evaluate by comparing rainfall temperature and daily volume against reservoir temperature & volume*

Specific guidance: hydropower

Although hydropower functions are theoretically very vulnerable to climate change due to the predicted hotter, drier summers and resultant impact on yields, in practice the impact on overall viability should be limited. Existing schemes are likely to have benefitted from increased income due to 'green' energy tariff policies, and for England and Wales it is unlikely that hydropower represents the sole energy supply to dependent users. Reductions in yield may therefore affect output, but are unlikely to affect the financial viability of schemes. Changes in supply and demand for energy should balance out due to higher summer versus lower winter demand, and they will tend to represent part of a wider regional energy balance, rather than an absolute impact on a discrete number of users.

Potential constraints

Yield: changes in reservoir yield, particularly where the hydropower is a secondary function for a water supply reservoir, could significantly affect water availability and hence output.

Demand: changes in demand for electricity could affect the viability or adequacy of the existing hydropower assets

Approaches to evaluating climate change impacts (see Section 3.2)

Yield (lower summer rainfall/higher temperature): See *storage for water use* for evaluation methods. Note that hydropower releases are normally included within the control curves for water supply and normally only occur at high water levels.

Demand (higher winter and summer temperatures: assume demand for electricity increases/decreases in line with higher summer and winter temperatures. See **Table 3.4** for guidance on calculating baseline and changes in heating/cooling days.

Considerations for possible 'tipping points'

Commercial viability (maintenance costs versus generating revenue). In practice this is unlikely to be an issue for existing assets.

Notes

None

Specific guidance: other (including effluent storage)

The main 'other' function relates to storage of effluents or other wastewater, often prior to final treatment and discharge. The nature, source and controls on discharge for these wastewaters will vary considerably, but outline guidance is provided below.

Potential constraints

Effluent/wastewater quality: changes in the quality of the stored effluent, leading to problems with treatment or ability to meet discharge consents.

Effluent/wastewater temperature*:* where biological treatment is used, then this might be affected by the temperature of the effluent.

Effluent/wastewater volume*:* exceeding maximum or minimum treatment capacities.

Capacity of receiving water course: changes in hydrological flows or receiving water quality leading to constraints on allowable discharges

Approaches to evaluating climate change impacts (see Section 3.2)

***Effluent/wastewater quality* – highly variable**: Consider implications of climate change on sources. If the reservoir has a catchment, then dilution capacity will be reduced. See **Table 3.4** for outline guidance on water quality.

Effluent/wastewater temperature – ***highly variable****:* Consider implications of higher summer temperatures on the heating of the stored water, and the implications on the effluent entering the reservoir. Ongoing UKWIR research(CL08) indicates that effects are unlikely to be significant.

Effluent/wastewater volume – **highly variable**: Impacts on sewage volume and quality are not yet available, but guidance will be provided when the UKWIR CL08 project is published.

Capacity of receiving water course (summer rainfall, higher temperature). In practice it is very unlikely that the undertaker will be required to carry out any evaluations of the capacity of the receiving water course; this would be done by the regulatory authorities. The change in capacity should be broadly proportional to changes in flow (See **Section 3.2.2.3)**

Considerations for possible 'tipping points'

Failure of treatment capability with associated risk of not meeting discharge consents. It is likely that advanced warning and planning will be required to develop the adaptation measures that are required if this is a risk (measures could involve a change in upstream operation and/or modification of treatment works).

Notes

None

Guidance on adaptation pathways for function

The process for evaluating adaptation responses for function is similar to that described for form. The following stages are recommended for the evaluation:

- Review the severity of the constraints and the timescales over which impacts might occur,
- Determine if any additional monitoring is required to understand the more significant constraints before they become problematic (particularly where there may be a risk of 'tipping points'),
- Determine what pro-active maintenance or changes in operation could be implemented to defer or prevent impacts,
- Consider potential capital works or changes in function that may be required to adapt to climate change impacts.

The adaptation measures for function are more likely to involve a number of stakeholders or owners and may be less 'engineering based' than those for form. When determining the adaptation pathways assessors should consider how management and institutional arrangements might affect the possibilities and implementation of the adaptation measures. The assessment of the 'decision context', as described in **Section 6.3.1,** is a key part of this process.

Unlike form (which is largely driven by safety requirements), adaptation pathways for function will depend on the costs involved when compared to the benefits that the owners will receive from enhanced monitoring, operational changes or preventative maintenance. This decision will depend on the evaluation of the level of impact and the value of the existing functions to the reservoir owner. When making this decision, the assessor should consider the implications that stopping secondary functions might have on management, operational and maintenance costs for the form of the dam or other reservoir functions (e.g. maintenance of the reservoir margins may deteriorate if boating or fishing activities cease).

Actual adaptation measures are highly variable and some examples are provided in **Appendix F**. In general, these cover:

- Monitoring of frequency of use and water levels,
- Monitoring of attributes such as water temperature/quality or changes in the type and health of marginal/catchment vegetation,
- Changes in control curves or other operational rules,
- Changes to restrictions on fishing/recreational seasons,
- Modifications to the operation of treatment processes,
- Increased dredging/other maintenance, planting to increase shading or marginal vegetation, changes in vegetation management regimes,
- Minor changes to function such as types of boating activity or changes from trout to coarse fisheries,
- Changes to catchment management practices,
- Remedial works such as trash screens, increased capacity, extended slipways, new or extended treatment works.

7. Conclusions and recommendations

Overall, this evidence based review has found that dam form (i.e. the embankment structure, spillway and ancillaries) is relatively resilient to the direct effects of climate change. There is also a well structured, well understood process under the Reservoirs Act 1975 that provides for periodic review of surveillance and maintenance requirements in a manner and timescale that is generally suited to climate change adaptation. Some reservoir functions (i.e. the use that the reservoir is put to) may be relatively vulnerable to climate change, particularly where they rely on existing yields, flood flows or water quality of source waters. However, there are a number of systems that are already in place (e.g. the Water Resources Management Plan) that contain methods for identifying impacts and adapting to climate change as part of the normal ownership and operation process.

Nevertheless, dams and reservoirs are complex, large scale assets which vary significantly in both form and function. This size, complexity and variability mean that potential vulnerabilities to climate change do exist. Often these result from separate effects on the catchment, dam structure and/or function that combine to present a specific impact mechanism or constraint for the dam or reservoir.

This guidance therefore concentrates on the approaches that are needed to ensure that climate change adaptation within this sector can be achieved through enhancement of the monitoring, operation and maintenance regime that already exists for the current reservoir stock. It has been developed to allow dam owners to engage suitably qualified practitioners to carry out straightforward, periodic, risk based assessments of the impact of climate change on dams and reservoirs that are designed to fit in with the existing regulatory process. A key part of the guidance has been to present the assessment in a way that will promote lateral thinking in practitioners, whilst at the same time providing clear references for simple assessments where these are appropriate.

Because of the relatively wide ranging and complicated nature of the potential impact of climate change on dams and reservoirs, it is generally recommended that the assessment process is coordinated by either the Supervising Engineer or another similarly qualified Civil Engineer that is familiar with the existing nature and operation of the dam. This person should be responsible for assessing the potential impacts and adaptations required for the dam form, and for ensuring that these are coordinated with the assessment and adaptation measures required for dam function.

Dams with erodible (earthfill) embankments are most likely to be vulnerable to climate change where increased erosion, more extreme fluctuations in water levels, changes in vegetation and prolonged drying during hot weather could combine to exploit existing weaknesses that may exist in the dam design or construction. Some of these weaknesses may already be known about but do not present a significant risk under current climatic variation, whilst others will only become apparent over time. The form of non-erodible structures (concrete, masonry etc) is unlikely to be particularly vulnerable to climate change, but there are exceptions, particularly at dams where existing climatic variation is known to cause problems associated with cracking or joint movement.

Overflow structures and spillways may also be vulnerable due to increasing frequency and size of flows, and catchment impacts that might increase debris and vegetation. Auxiliary structures such as valves or draw off towers may be vulnerable to similar effects and can be prone to other factors such as siltation or heat induced expansion. Again, problems may occur due to the exacerbation of known, existing issues, but in some cases the vulnerability will only become apparent over time.

Dam function can be affected in a variety of ways, including more ‘obvious’ impacts such as changes in hydrology or water quality and less apparent issues such increasing water level fluctuation leading to a deterioration in marginal vegetation conditions and hence bankside fishery functions. Such issues need to be evaluated through a combination of approaches, ranging from predictive modelling (for hydrology/yield or water quality) to trend analysis or simple analysis of change factors by operators that are sufficiently familiar with the reservoir and catchment. The existing operational and management regime associated with the various dam functions can affect the nature of the impacts and the type of adaptations that may be possible, so it needs to be considered when climate change is being evaluated.

Because of the variety of effects and timescales involved with climate change impacts at dams and reservoirs, the adaptation measures that have been recommended within this guidance generally follow a 'plan' format, which involves an escalation of measures over time. Changes or enhancements to monitoring and surveillance form the first stage, and will be sufficient for many dams and reservoirs. In terms of form, these should tie in with the existing inspection regime. Where appropriate, monitoring should be accompanied by preventative maintenance measures (e.g. changes in the grass cutting regime). Reactive maintenance and capital works can then be planned as necessary as the situation evolves and monitoring data support the need for such adaptation measures. Finally, in some cases it may be necessary to change functions or even decommission the dam in the face of climate change, but the monitoring measures and timescales involved should mean that there will be sufficient warning to properly plan for any such changes.

In terms of the general policy and planning that surrounds dams and reservoirs there are already a number of initiatives that are in place to reduce demand (for pubic supplies and hence seasonal storage requirements for reservoirs) and runoff during flood events, which will help with general adaptation as climate change increases stresses on form and function. However, it was noted that the following issues should also be considered in relation to planning and policy:

- Policies and regulations relating to compensation flows and discharge consents should consider climate change when these are being reviewed. This includes the processes that govern the implementation of drought orders to reduce compensation flows. Climate change will tend to increase the stress on reservoir yield, so faster implementation of drought measures will become more important over time.
- Climate change should be considered when planning controls and policies are being reviewed, as climate change will tend to increase the need for new dams and modifications to existing structures. Design measures that are implemented at dams and reservoirs to improve their acceptability in planning terms need to consider the impact of climate change, and planning authorities need to be aware that this may reduce mitigation options within the application.
- Climate change impacts on reservoir catchments should be considered when policies relating to land use are being formulated or reviewed. The main issue relates to a potential deterioration in water quality, so land use policies and guidance that support catchment management measures to reduce siltation and diffuse pollutants such as BOD, nitrates and phosphates would be advantageous.

For practitioners that are involved in the planning of new reservoirs, many of the implications of climate change relate to hydrology and demand forecasting, which are reasonably well covered through the existing guidance that has been summarised within this report. Planners also need to consider how climate change might affect proposed secondary functions within the reservoir, and understand the types of catchment management practices and management regimes that need to be applied in order to ensure sustainability of the reservoir under climate change.

In terms of the design of new reservoirs, the risk factors and design considerations that generally need to be followed are largely covered by the main guidance on monitoring and maintenance of the existing dam stock. The design standards that exist in the UK are generally sufficient and allow for the effects of climate change, but in some cases reference to international standards (e.g. ACI standard 305R - Guide to Hot Weather Concreting) may be advisable during construction if some of the extremes of climate change start to be realised.

Final guidance on the implementation of the risk based approach for the regulation of dams and reservoirs, as required under the Flood and Water Management Act 2010, is not available at the time of writing this guidance and it is strongly recommended that the guidance is renewed once it is available.

The structure and approach of this guidance has been developed to be generally compatible with the expected outputs from those reports, so their inclusion should be straightforward.

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Appendix A Technical notes on aspects of climate change

A.1 Reporting requirements

A.1.1 Adaptation reporting

The Climate Change Act 2008 gives the Secretary of State the power to require certain organisations to report on the current and future risks to their activities from climate change and propose a plan of how to adapt to these risks. These organisations are known as 'reporting authorities' and encompass bodies who have functions of a public nature and statutory undertakers; the latter of these includes all water and energy companies operating in the UK. Though this list of reporting authorities includes over 100,000 organisations, a selection of 'priority reporting authorities' were requested to complete the reporting. In addition, a number of organisations have agreed to report voluntarily including Natural England, the Forestry Commission and a number of National Park Authorities.

Defra has issued statutory guidance on how the reporting should be completed and presented, stating that it should include (Defra, 2010a):

- A summary of the statutory and other functions of the reporting authority to ensure that they are taking into account the risks presented to all their functions,
- An assessment of the current and predicted risks to that organisation, or its functions, presented by climate change,
- A programme of measures to address the risks highlighted above including any policies or practices that are already being implemented.

In addition, the Environment Agency – which is itself a priority reporting authority – has issued supplementary guidance for reporting on water resources, flooding and coastal change.

Authorities were required to report to Defra by 31st January 2011. The reports are being evaluated by Cranfield University against the statutory guidance and also commented on by Defra and other relevant government departments. The completed reports are expected to be published on the Defra website by the end of 2011. This process will continue on a rolling five-year cycle of reporting.

A.1.2 National climate change risk assessment

As part of the Climate Change Act, the UK government is committed to undertake a national risk assessment on climate change every five years, which is reviewed by the independent Adaptation Sub-Committee of the Committee on Climate Change. The first of these risk assessments is currently being drafted and must be presented to Parliament by 26th January 2012.

The purpose of the risk assessment is to provide UK administrations with information to (Defra, 2010b):

- Understand the level of risk (opportunities and threats) posed by climate change for the UK, where risk is a consideration of the likelihood of an impact and the magnitude of the consequences,
- Compare the risks posed by a changing climate with other pressures on the Government,
- Prioritise adaptation policy,
- Assess the costs and benefits of adaptation actions.

In response to some of the key conclusions of the Stern Review, the risk assessment will also include an Adaptation Economic Analysis (AEA) to provide an indication of the costs of adaptation in the UK (both the expenses and the benefits it will bring) and identify the areas for which most benefit can be brought.

The risk assessment is undertaken by sector (water, flooding, biodiversity, etc); the water and flooding sector reports are being led by HR Wallingford. Both these sectors will cover the risks to dams and reservoirs and will include potential adaptation options for dam owners to consider.

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A.2 Leisure conditions and heat stress

A.2.1 Leisure conditions

With increasing summer temperatures, northern European countries such as the UK may become more desirable for summer holiday locations, offering warm conditions that may be preferable if the traditional Mediterranean destinations become uncomfortably hot in the summer (Hamilton *et al*., 2005a; Hamilton *et al*., 2005b; Bigano *et al*., 2007). Domestic day trips are also likely to become more popular with hotter summer conditions; good weather is a trigger for short outings on weekends and bank holidays (McCabe, 2000). The heatwave in July 2006, for example, saw very high numbers of visitors at various outdoor events including the Open Championship at Royal Liverpool golf course and the Farnborough Airshow, as well as large numbers visiting the UK's beaches (BBC, 2006).

A.2.2 Heat stress

Hotter summer temperatures also increase the risk of heat stress health problems such as heat exhaustion and heat stroke in both tourists and workers. Serious heat stroke occurs when the core body temperature exceeds 39.4°C, which can lead to multiple organ dysfunction from which death can occur within hours (Kovats & Hajat, 2007). In the 1995 heat wave in the UK, for example, an estimated 619 deaths were observed above the number of expected deaths for that period (Rooney *et al*., 1995). The heat wave in the summer of 2003 resulted in 14,802 deaths in just 20 days in France (ibid). UKCP09 shows an increase in maximum daily temperature across the country (e.g. by 3.7°C for the central estimate under Medium emissions in the 2050s for southeast England[6]) and with an increasing risk of extended spells of hot conditions, heat-related health problems are likely to become more of an issue in the UK.

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6 http://ukclimateprojections.defra.gov.uk/content/view/2262/499/

A.3 Mosquito borne disease

There are around 30 species of mosquito that are found in the UK – predominantly throughout summer and autumn. Mosquitoes breed in standing water and so reservoirs are an obvious habitat for them. Their larvae float just below the surface of the water, allowing them to breathe oxygen (through a small tube) and also feed on organic particles in the water. Larvae tend to take around 8 to 12 days – depending on conditions and the species – to mature into an adult mosquito.

Mosquitoes are very effective vectors for diseases; females must feed on a blood meal before laying their eggs – which they may do up to six times in any one season – and so can transfer infections between those they bite. Both the development of the parasite/virus in the mosquito and the survival of the mosquito itself are highly influenced by temperature, with warmer conditions allowing an infected mosquito to become infectious more quickly (Sherman, 1998).

A.3.1 Malaria

Malaria is an infectious disease caused by the parasite *Plasmodium* and spread predominantly by the *anopheles* mosquito, of which several species are common to the UK. Cases of locally-contracted malaria in the UK gradually decreased through the 19th century as marsh and fenlands were drained, sanitation improved and densities of livestock increased (providing alternative blood meals from humans) (Kuhn *et al*., 2003). By 1910, no deaths from malaria were recorded at county level (ibid). However, in modern times, several thousand cases of 'imported malaria' are recorded every year as a result of travellers returning from malarial areas overseas – particularly Africa (Smith *et al*., 2008).

At present, the likelihood of a secondary infection of malaria in the UK is extremely small as primary cases from those returning from abroad are treated very quickly, removing the possibility of a subsequent infection (the last recorded secondary case was in 1953 (Kuhn *et al*., 2003)). Whilst a temperature rise of 1 to 2.5°C by the 2050s may increase risk of local infection by 8-15%, unless there are widespread drug resistance problems, it is highly unlikely that this would result in a re-establishment of endemic malaria in the UK (ibid).

A.3.2 West Nile virus

West Nile virus is an arbovirus (i.e. **ar**thropod-**bo**rne) which predominantly affects birds but can also be spread to humans and horses via a bite from an infected mosquito (Buckley *et al*., 2003). It is spread by the *Culex* mosquito, of which the species *Culex Pipiens* is the most common mosquito in the UK. The virus is found in much of Africa, central Asia and the Middle East and has recently spread to America, first appearing in New York State in 1999 and then spreading into western states in warmer years. It is now endemic to 47 of America's 50 states, with 3,510 cases and 109 deaths in the US in 2007 (Soverow *et al*., 2008).

Because it infects birds, it is likely that a primary method of disease spread is via migratory birds, while humans and horses are dead-end hosts – i.e. there is no spread of the disease on to others (Defra, 2009). The virus has been identified in birds and horses in other European countries including France, Italy and Romania (Buckley *et al*., 2003). A study of 30 different species of birds in the UK found specific antibodies of West Nile virus, suggesting the virus had been introduced to UK-resident birds from migratory birds, though no actual disease incidence has been reported (ibid). At present, the risk to health in the UK would appear to be small – especially as the UK experiences a lower average temperature and lower density of mosquito population than the US, for example (ibid). However, with climate change, the UK could be at risk from a similar spread of West Nile virus that has affected America over the past decade. A study of that spread showed the disease incidence was positively associated with both higher temperatures and periods of heavy rainfall – both of which are projected for the UK (Soverow *et al*., 2008).

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A.4 Extreme rainfall and floods

A.4.1 PMP and PMF

A warmer climate is expected to result in a greater intensity of the hydrological cycle as both evaporation and precipitation increase (Senior *et al*., 2002). However, the extent to which mean rainfall and heavy rainfall totals changes is less clear; more intense rainfall is consistent with greater storminess in winter and greater convective activity in summer, but climate models do not always agree to the magnitude and sign of changes (ibid). Modelling studies show an increase in extreme rainfall in winter that is larger than the corresponding increase in mean rainfall, and that also has a stronger signal than for changes in mean precipitation (Kendon & Clark, 2008). Summer changes in extreme rainfall are more uncertain (models differ with regard to magnitude and sign of the changes) as they tend to feature more localised, convectional events, which are not captured well by climate models (ibid).

Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) are two metrics that are often used in dam design. PMP refers to the highest amount of rainfall a particular area can theoretically receive for a given duration of storm; PMF is the flood that would arise from PMP for a critical duration (Collier & Hardaker, 1996). Dams are therefore constructed to ensure they can cope with a certain percentage of PMF, depending on the consequences of failure.

Research on the impact of climate change on PMP and PMF is limited; it was considered as part of the Flood Risk from Extreme Events (FREE) programme coordinated by NERC (Natural Environment Research Council). Research by FREE showed 1-hour rainfall accumulations increasing by 7% with every degree of temperature rise, though this rate slows above 25°C; it was also shown that 8-hour accumulations actually decreased with temperature (Collier, 2009).

A.4.2 Design storms and floods

Applications in terms of changes to design storms have tended to focus on sensitivity testing (e.g. for Catchment Flood Management Plans) underpinned by Defra/Environment Agency guidance. The latest Environment Agency (2011) guidance provides indicative sensitivity ranges for peak rainfall intensity and regional change factors for peak river flows (the latter building on Reynard *et al*., 2009).

Return period analysis is also common in studies assessing heavy rainfall and associated flood risk. For example, a study by Huntingford *et al*., (2003) found that 30-day rainfall maxima for a 1 in 20-year event (5% chance of occurrence per year) in 1860 would become a 1 in 2- or 3-year event by 2090 (30-50% chance of occurring per year) for York, Shrewsbury and Lewes. However, such results are specific to each catchment and therefore broad statements on changes across the country should be used with caution.

Methods exist for perturbing design flood flows to account for climate change (for example Darch and Jones, 2012) but they are limited by the ability of climate models to accurately reproduce and simulate extreme precipitation.

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A.5 Vegetation growing conditions

A.5.1 Growing degree days

Growing degree days (GDD) is described as the cumulative daily sum of the number of degrees by which the mean air temperature is greater than a given threshold (typically 5.5°C for many cereals). It provides an indicator of the suitability of a climate for a particular plant or insect, the potential growth stages and potential issues with heat stress and pest interaction. With increasing temperatures, it is likely that the plants could mature and flower earlier in the year, but this may also have benefits for pests.

UKCP09 does not assess the impact of climate change on GDD in the UK. However, for more detailed analyses, it would be possible to use the UKCP09 Weather Generator to carry out a quantitative assessment of changes in GDD. The Weather Generator includes a 'threshold detector' post-processing tool, which allows users to assess the Weather Generator output for how often daily weather crosses a given threshold and produces summary statistics across all the Weather Generator runs.

A.5.2 Thermal growing season

While there is no assessment in the change of growing degree days in UKCP09 or UKCIP02, the latter does cover the change in thermal growing season, which is described as the longest period within a year that begins when daily-average temperature is greater than 5.5°C for five consecutive days and ends when daily-average temperature is less then 5.5°C for five consecutive days (Hulme et al., 2002). The length of the thermal growing season for the baseline period (1961-1990) ranged from less than 160 days for parts of the Scottish Highlands to more than 300 days for the south and west coasts of England and Wales[7]. It has increased by about a month over the 20th century for central England; this is mostly a result of the earlier onset of spring but also the slightly later onset of winter (ibid). Projections for the 21st century show further lengthening of the season for all of the UK by at least a month and up to three months in the southeast under High emissions resulting in year-round thermal growing conditions.

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[7] Based on the UKCP09 5km gridded long-term averages (see http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09)

A.6 Vegetation growth, pests and diseases and non-native and invasive species

Plant growth function is linked to climatic factors such as temperature, precipitation and carbon dioxide concentration and the interaction between these factors. Climatic variables affect plants at a range of scales, from altering the physiological processes within individual plants to determining community distribution and composition at a planetary scale (Morrison and Morecroft (eds) 2006). In dam and reservoir systems vegetation can play an important role in stabilising the dam face but also affects the amount, rate and quality of water entering the system. In some reservoir systems plants also play an important aesthetic role.

Vegetation can be adversely affected by disease and the activities of non-native or invasive species. Pests and diseases have close relationships with climate, and many will thrive under warmer conditions and wetter winters. Invasive species are often bigger, faster growing or more aggressive than native species with few natural predators and can upset the balance of ecosystems (Environment Agency 2010). Many invasive species are non-native species, i.e. plants or animals which have been introduced to a place where they do not naturally occur. Invasive species can also be native species which grow well in disturbed or nutrient-enriched conditions, to the detriment of other plant and animal species (Environment Agency 2010). The growth and distribution of invasive species is directly affected by climate variables such as temperature and precipitation but also by indirect effects of climate change such as changes in water quality and recreation demand. In dam and reservoir systems, invasive species can reduce water storage capacity as well as increasing flood risk if they grow on reservoir margins.

A.6.1 Climate change and vegetation growth

The affect of climate change variables on vegetation growth will be highly varied in time and space and will depend on the tolerance of individual plants to changes in temperature and precipitation. In general, warmer temperatures and longer growing seasons may result in an increase in vegetation growth where growth is not limited by moisture availability. In a meta-analysis of data on above-ground plant productivity in four biomes (high tundra, low tundra, grassland and forest), Rustad *et al* (2001) found that warming in the range 0.3-6.0°C produced an increase in plant productivity of 19%.

In an experiment to measure plant growth associated with warming in shrubland ecosystems in Europe (UK, Denmark, the Netherlands and Spain), Penuelas *et al.* (2004) found that after two years of approximately 1°C warming, above-ground plant biomass growth increased by 15% in the UK site. The study concluded that in northern sites which tend to be temperature-limited, direct and indirect effects of warming such as longer growing season and increased nutrient availability, are likely to result in an increase in above-ground biomass growth (Penuelas *et al*. 2004). However, in southern sites where temperature is already close to the optimum for photosynthesis and water availability is the limiting factor in growth, warming is unlikely to result in increased plant growth. The study also found that plant processes were more sensitive to warming during the winter than during the summer (Penuelas *et al*. 2004).

In addition to warming, plant growth may be accelerated due to an increased concentration in atmospheric carbon dioxide. An increase in carbon dioxide can result in an increase in the rate of photosynthesis and a decrease in the rate of transpiration from leaves (Poorter and Navas 2003). This can stimulate plant growth, although most experiments show that any increase in growth is a short term phenomenon, strongly coupled to other factors such as availability of water and nutrients (Solomon *et al*. 2007).

Whilst there is some experimental evidence to suggest that vegetation growth in the UK will increase as a result of climate change, this will depend strongly on specific factors such as community composition, site quality, successional state and land-use history.

The distribution of vegetation is influenced by climatic factors (as well as non-climatic factors such as dispersal ability). In the UK, hotter, drier summers and warmer, wetter winters may change the range of plant species: species currently at the northern limit of their range may expand, and species at the southern limit of their range may retreat (Walmsley *et al*. 2007). The Modelling Natural Resource Responses to Climate Change (MONARCH) project simulated the future climate space of 32 Biodiversity Action Plan (BAP) species, including a number of aquatic and riparian plants. Suitable climate space for cut-grass *Leersia oryzoides* is projected to increase until the 2080s when high temperatures and increased occurrence of summer drought may reduce its preferred habitat (Walmsley *et al*. 2007). Floating water plantain *Luronium natans* is projected to increase its range in northern Britain but suitable climate space will be lost in the south (Walmsley *et al.* 2007).

Phenology is the study of the timing of recurring natural events e.g. the arrival of spring, blossoming, leaf fall and flowering. Many of these natural events are influenced by climatic factors and their timing is likely to be affected by climate change. One of the UK Government indicators of climate change is budburst of oak. The UK Phenology Network has recorded evidence of phenological change, in particular the early arrival of migrants, early flowering or leafing dates and delayed leaf fall (Collinson & Sparks, 2003, 2005; Sparks and Collinson, 2006).

A.6.2 Climate change and pests and diseases

Warmer conditions are likely to make pests more prevalent due to a quicker life cycle and the ability to overwinter as adults. Increased carbon dioxide concentrations may reduce the susceptibility of plants to attack, but due to the impact on nitrogen concentrations, insects may increase consumption, although a reduction in water availability will concentrate food supply (Bisgrove and Hadley, 2002). Pests and diseases affecting trees, such as the horse chestnut leaf miner moth *Cameraria* which is prevalent in other European counties, may become more prevalent in the UK. Beech, which is susceptible to drought, may be further affected by mammals such as roe deer and grey squirrels (ibid.).

The impact of climate change on plant diseases is complex but Bisgrove and Hadley (2002) have summarised the general impacts as follows:

- Wetter, warmer winters will favour diseases such as *phytophthora* that need water to spread,
- Drier, warmer summers will favour disease such as powdery mildew that can spread in dry conditions,
- Warmer conditions will allow diseases that cannot establish under current climatic conditions in the UK to survive and establish, but will cause the decline of existing diseases unable to adapt to higher temperatures,
- Impacts will include damage to trees, particularly those already stressed by drought.

A.6.3 Climate change and non-native and invasive species

Defra define invasive non-native species as 'any non-native animal or plant that has the ability to spread causing damage to the environment, the economy, our health and the way we live' (Defra 2010). A possible implication of increased vegetation growth due to a warmer climate is that non-native invasive species may become an increasing problem in the UK. Reservoirs can be hot-spots for non-native species (Rahel and Olden 2008) including killer shrimp *Dikerogammarus villosus*, curly water weed *Lagarosiphon major*, New Zealand pygmy weed *Crassula helmsii* and zebra mussels *Dreissena polymorpha*.

Currently, many non-native invasive aquatic species are curbed to some extent by frost events and winter hypoxia which prevent survival (Rahel and Olden 2008). Warmer winters and fewer frost events could result in non-native invasive species surviving the winter, allowing them to out-compete native species. A change in climate conditions could put stress on native species, making them more vulnerable to competition from non-native invasive species. An increase in non-native species may also increase the risk of disease for native species, e.g. a number of non-native amphibian species carry the chytrid fungus *Batrachochytrium dendrobatidis* which causes Chytridiomycosis, a disease which has been linked to declines of native amphibian species such as natterjack toad *Bufo calamita*.

A warming climate has the potential to change the range of some non-native species, increasing the probability that they will arrive in the UK. Warmer conditions may also lead to the development and spread of populations of non-native species already present in the UK but currently constrained by the temperature (Parrott *et al*. 2009). Parrott *et al*. (2009) carried out a horizon scanning exercise to identify potential non-native species that have the potential to become invasive in England in future. A 'Climate List' of species with high or medium risk of environmental damage but physiologically constrained from establishing in England without climate warming was identified and includes cane toad *Bufo marinus*.

A.6.4 Vulnerable species

The impacts of climate change are complex and depend on inter-relationships between elevated carbon dioxide levels, temperature, precipitation, seasonal and inter-annual variation in climate and a range of indirect and non-climatic factors such as land-use, habitat quality and connectivity. Of particular relevance to dams, reservoirs and their catchments are trees, grasses and water storing habitats such as bogs (see the section on water quality for a discussion on algae).

The impact of climate change on trees in the UK has been extensively investigated by Forest Research. The impacts are summarised in Ray *et al*. (2010) and include:

- Reduced summer tree growth where soil moisture deficits are high,
- Potential for enhanced growth due to higher temperatures and carbon dioxide concentrations,
- Reduced tree stability on exposed sites and an increased risk of windthrow,
- Increase in the incidence and severity of pests and diseases,
- Greater risk of fire.

The impacts of temperature and moisture deficit on species suitability (in terms of yield) show significant shifts by the end of the century (see Table 1 in Ray *et al*., 2010). For example Sitka spruce becomes marginal or unsuitable whilst Corsican pine remains suitable in the south and becomes very suitable in the north. The impacts on native woodlands (see also Table 2 in Ray *et al*., 2010) show for example a north and westward movement of beech woodlands with some replacement by pedunculate oak, a change in the composition and range of lowland mixed broadleaf woodlands, favouring beech and sycamore and a change in upland oak woodlands to become more like lowland woodlands.

Grasses are generally resilient and recover even after prolonged dry spells. However, evidence from lawns suggest they may be very susceptible to compaction from saturation following very heavy summer rainfall events, which could lead to long-term damage.

Ombrotrophic bogs are likely to be vulnerable to climate change because seasonal rainfall variability is likely to increase and they may dry out in summer; this may reduce their water holding ability and lead to water quality problems.

A.6.5 References

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A.7 Water quality

A.7.1 Introduction

Climate change has the potential to alter the quality of water in reservoirs directly or indirectly via natural or pumped inflows. Many of the changes will be closely related to hydrological changes. In winter this may mean higher inflows (and potentially higher reservoir water levels), with greater leaching but also greater dilution. In summer there may be lower inflows and greater drawdown, with less dilution and more stagnant water. In addition to the effects of dilution and movement, interactions with soils will be important, as this will influence the loads of sediment, metals and nutrients to reservoirs; leaching caused by storm events following longer dry periods could cause significant water quality problems. Higher temperatures will also be significant, especially when combined with hydrological changes such as lower summer flows.

Water quality issues have the potential to affect many functions of a reservoir including water supply, recreation and habitat.

A.7.2 Potential changes

The following is a summary of potential changes to reservoir water quality collated from the stated sources and ongoing research by Atkins for UKWIR:

- Increased risk of algal blooms in summer as a result of lower level, more stagnant water with nutrient-rich inflows associated with storm events. Also an increased risk of cynobacteria,
- Increase in Dissolved Organic Cabon (DOC) due to larger or more frequent high flows (Clark, 2005),
- Greater sedimentation associated with storm events, particularly after prolonged dry periods where soils become very dry and loose,
- Increase in water temperature, leading to increases in pH and reductions in dissolved oxygen. Stratification of lakes is likely to be earlier, the turnover later and the thermocline deeper (Carvalho, 2003),
- Uncertainty regarding nutrient concentrations, reflecting the complex balance between leaching and dilution. However, an increase is likely during reservoir refill after prolonged dry periods,
- Increase in concentration of metals during storms after prolonged dry periods.

A.7.3 References

Carvalho, L. & Kirika, A. (2003) Changes in shallow lake functioning: response to climate change and nutrient reduction. *Hydrobiologia* 506, 789–796.

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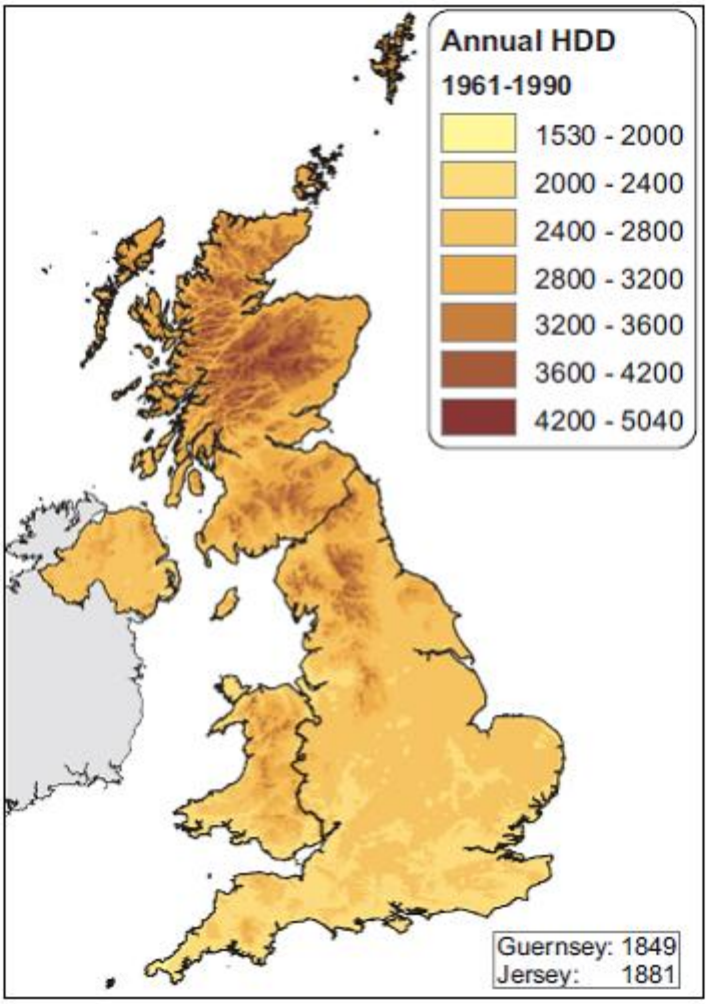
A.8 Heating and cooling

A.8.1 Cold weather energy requirements (Heating Degree Days)

Heating Degree Days (HDD) is an annual measure of the extent to which some form of building heating is required. To derive HDD, the number of degrees Celsius that the daily mean temperature is below 15.5 ºC is calculated for every day of the year (ignoring negative numbers, that is, when the mean temperature is above 15.5 ºC) and this is summed for all days of the year.

Baseline values for 1961 – 1990 are provided below.

Figure A.1 – Average annual heating degree days (HDD) for 1961 – 1990 ©Crown Copyright 2009



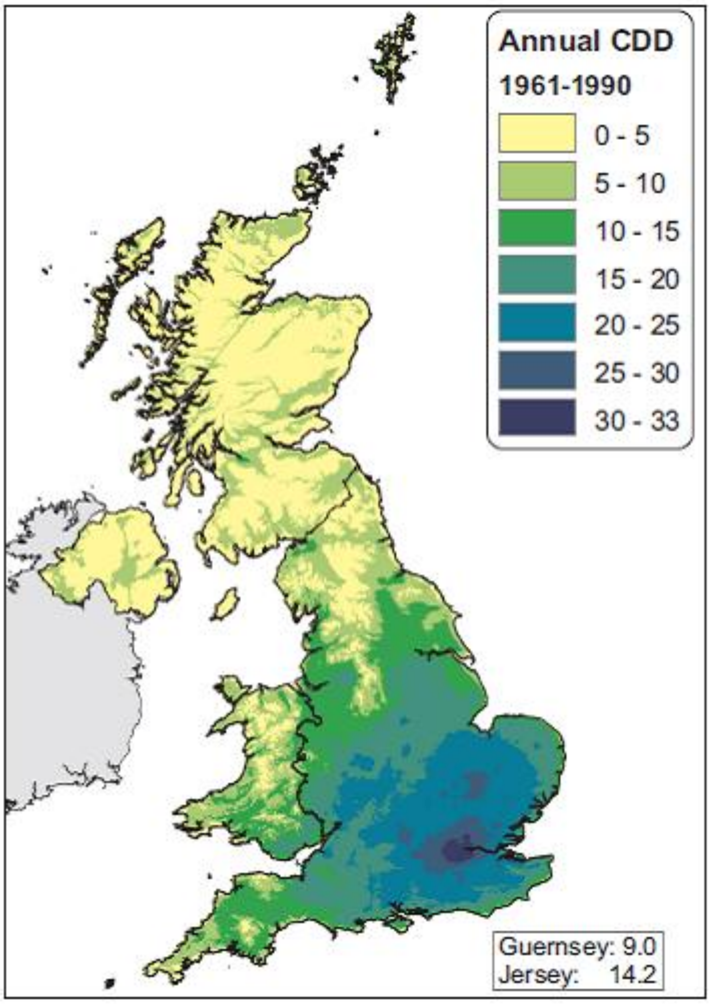
Under climate change, the number of HDDs will reduce in line with the increase in average temperature. The most appropriate way of calculating the impact is to run the online Weather Generator for a particular location and future period, over a period of 30 years around the chosen date (either 2050 or 2080). The HDD can then be calculated for that location using a 15.5ºC average daily temperature marker and the resulting HDD compared against the baseline value to derive the percentage change in heating energy requirements.

A.8.2 Hot weather energy requirements (Cooling Degree Days)

For offices, schools and living areas in homes, 25ºC is considered to be warm, 28ºC is hot. For bedrooms, the values are 21 and 25°C respectively. Heat stress risk occurs where indoor temperature is above 35ºC (for healthy adults at 50% relative humidity). In future the percentage time above these thresholds is expected to increase significantly, especially in London.

The most straightforward way to estimate cooling energy requirements in relation to baseline conditions is to use Cooling Degree Days (CDD), which is a similar measure to HDD. To derive CDD, the number of degrees Celsius that the daily mean temperature is above 22ºC is calculated for every day of the year (ignoring negative numbers, that is, when the temperature is below 22ºC) and this is summed for all days of the year. Baseline values for the period 1961 – 1990 are provided below.

Figure A.2 – Average cooling degree days (CDD) for 1961 – 1990 ©Crown Copyright 2009



Climate change will increase the need for building cooling. The approach that should be taken is the same as that described for HDD, using a threshold of 22ºC daily mean temperature.

A.8.3 References

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Appendix B Plume plots of changes in climate variables

B.1 Anglian River Basin

Figure B.1 – Plume plot of UKCP09 mean summer precipitation projections under High Emissions for the Anglian River basin: 2020s to 2080s inclusive. © Crown copyright 2009

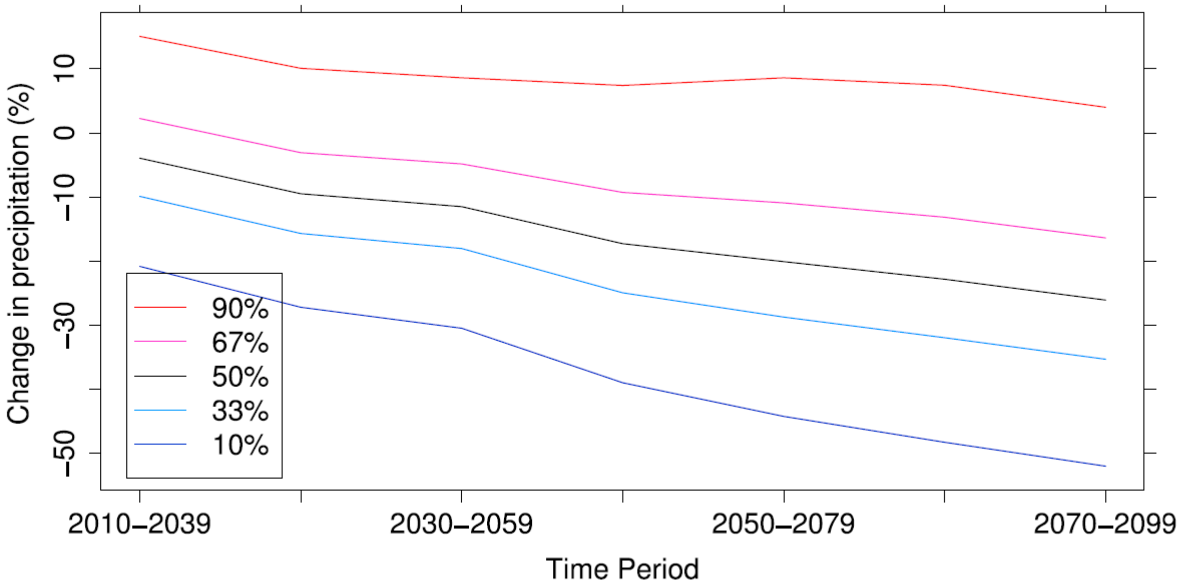


Figure B.2 – Plume plot of UKCP09 mean winter precipitation projections under High Emissions for the Anglian River basin: 2020s to 2080s inclusive. © Crown copyright 2009

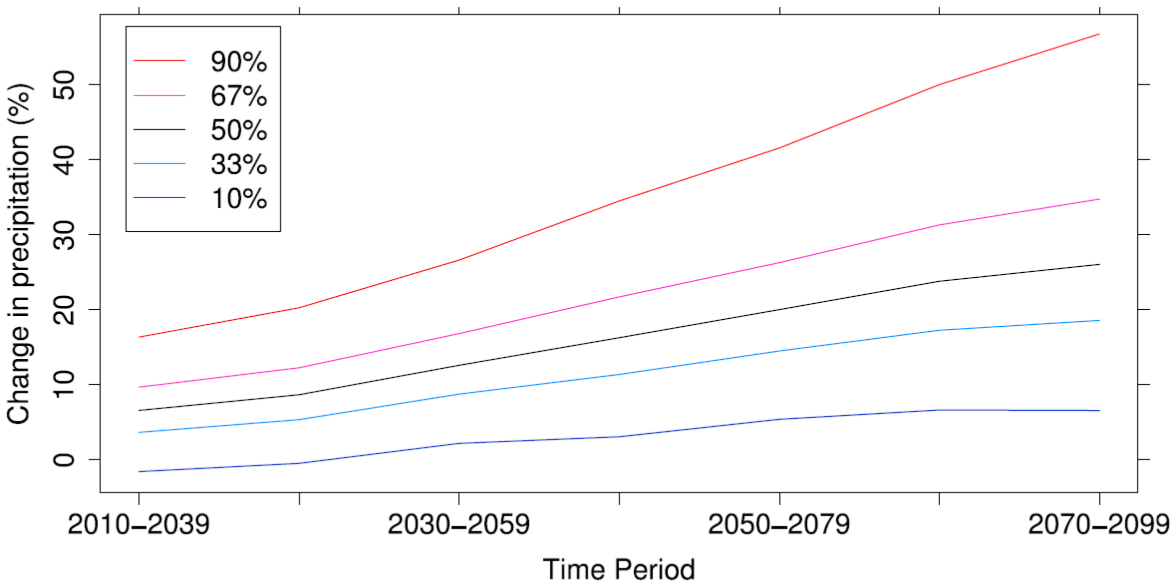


Figure B.3 – Plume plot of UKCP09 mean winter wettest day precipitation projections under High Emissions for the Anglian River basin: 2020s to 2080s inclusive. © Crown copyright 2009

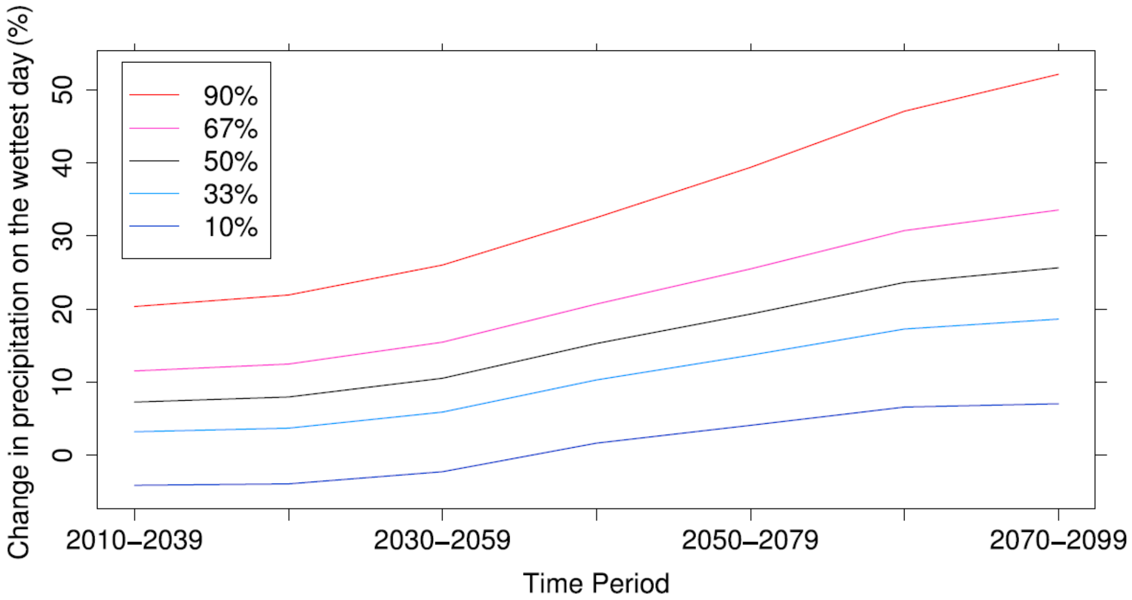


Figure B.4 – Plume plot of UKCP09 mean summer temperature projections under High Emissions for the Anglian River basin: 2020s to 2080s inclusive. © Crown copyright 2009

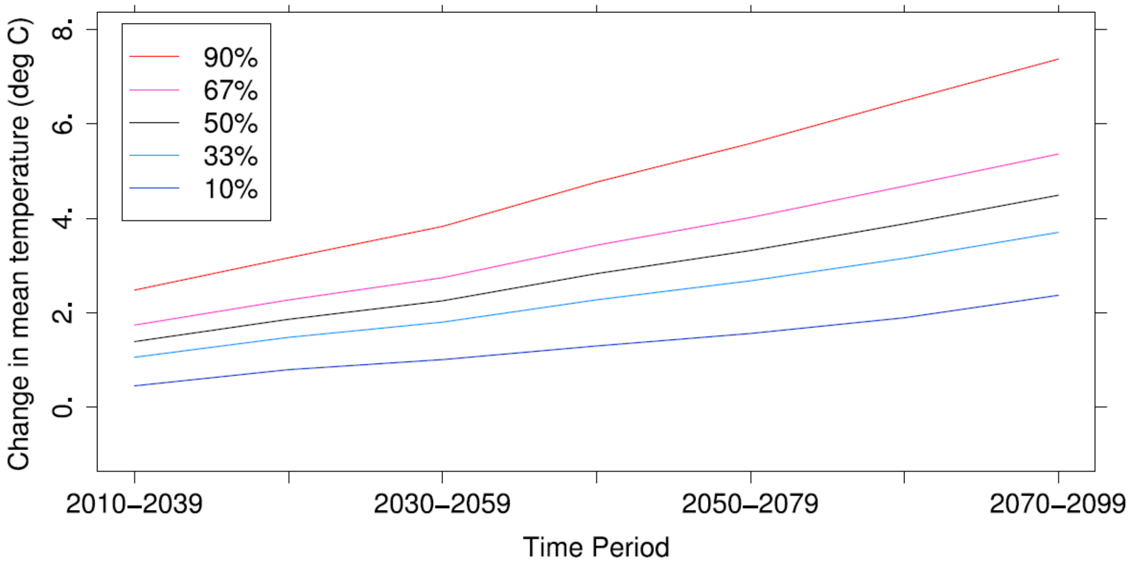


Figure B.5 – Plume plot of UKCP09 mean winter temperature projections under High Emissions for the Anglian River basin: 2020s to 2080s inclusive. © Crown copyright 2009

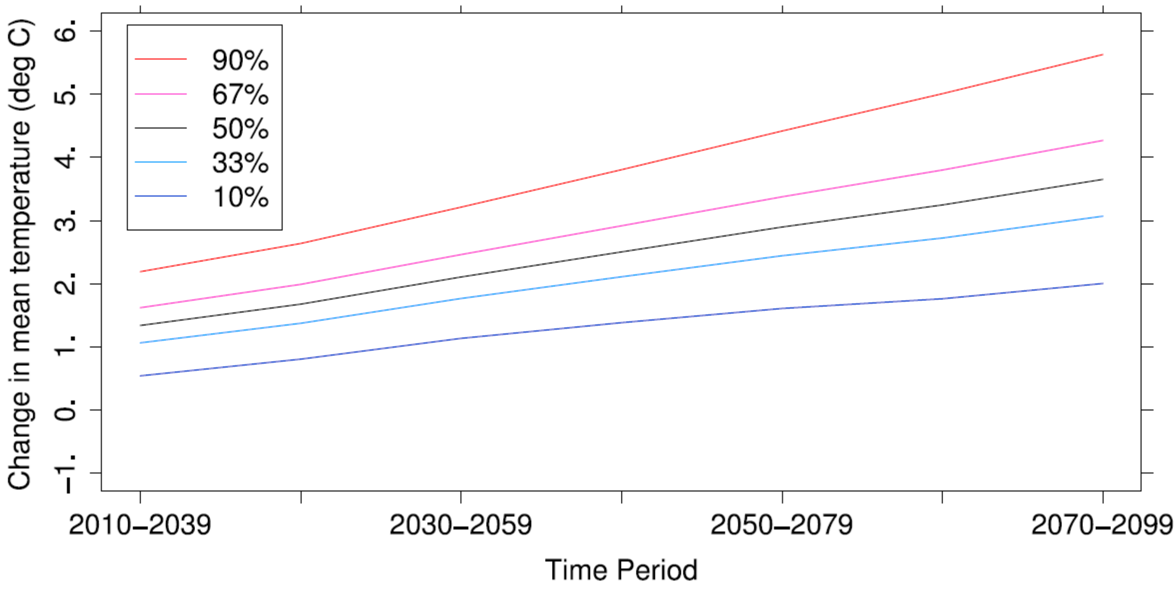
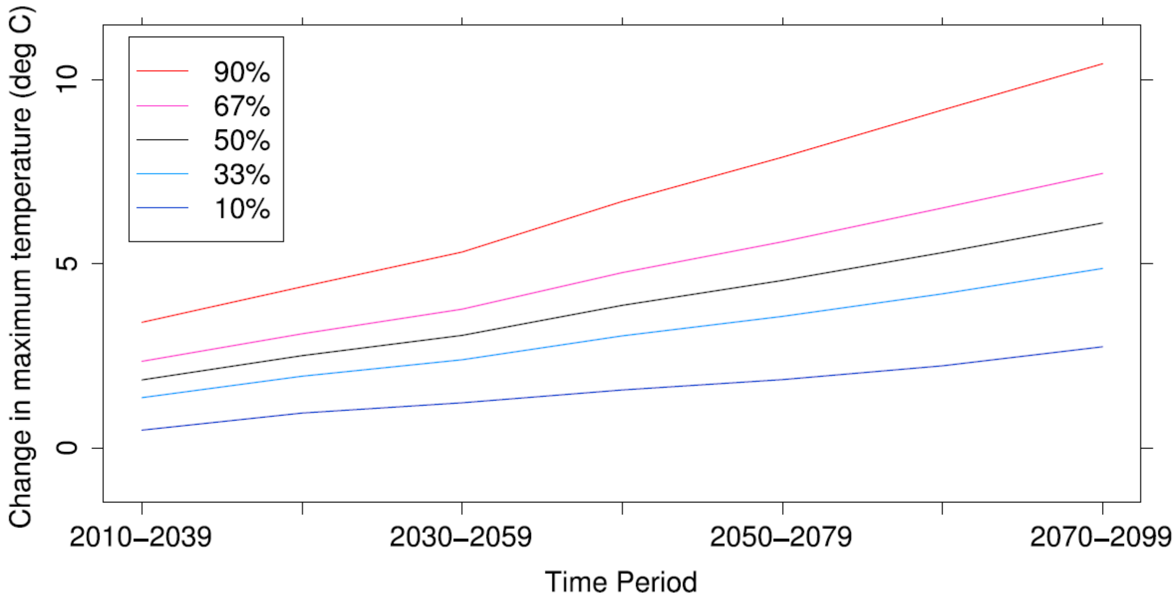


Figure B.6 – Plume plot of UKCP09 mean summer average daily maximum temperature projections under High Emissions for the Anglian River basin: 2020s to 2080s inclusive. © Crown copyright 2009



B.2 North West River Basin

Figure B.7 – Plume plot of UKCP09 mean summer precipitation projections under High Emissions for the North West England River basin: 2020s to 2080s inclusive. © Crown copyright 2009

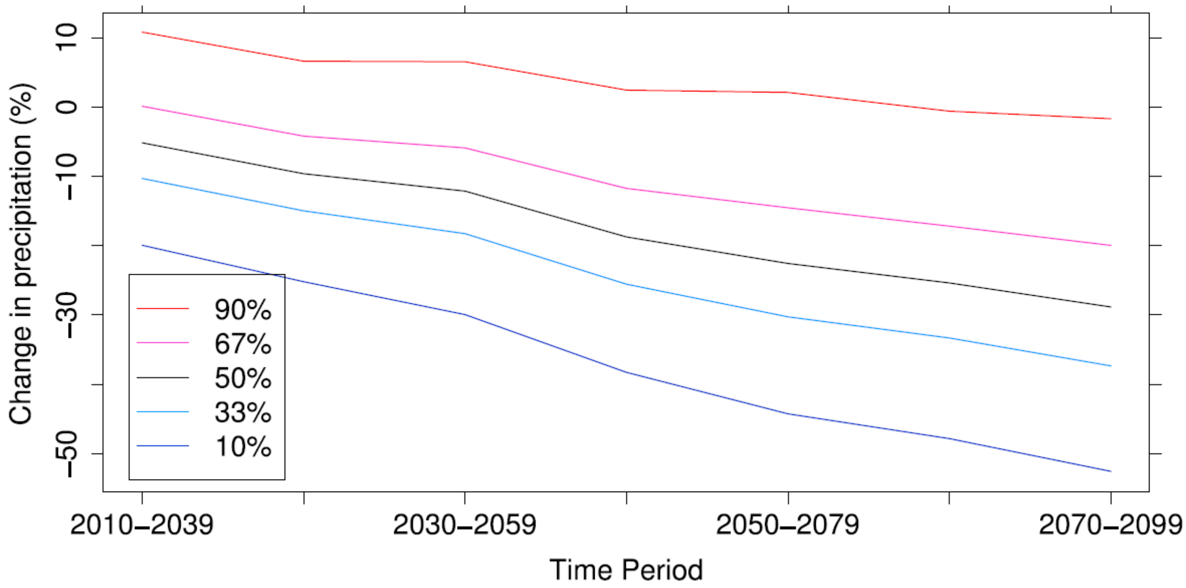


Figure B.8 – Plume plot of UKCP09 mean winter precipitation projections under High Emissions for the North West England River basin: 2020s to 2080s inclusive. © Crown copyright 2009

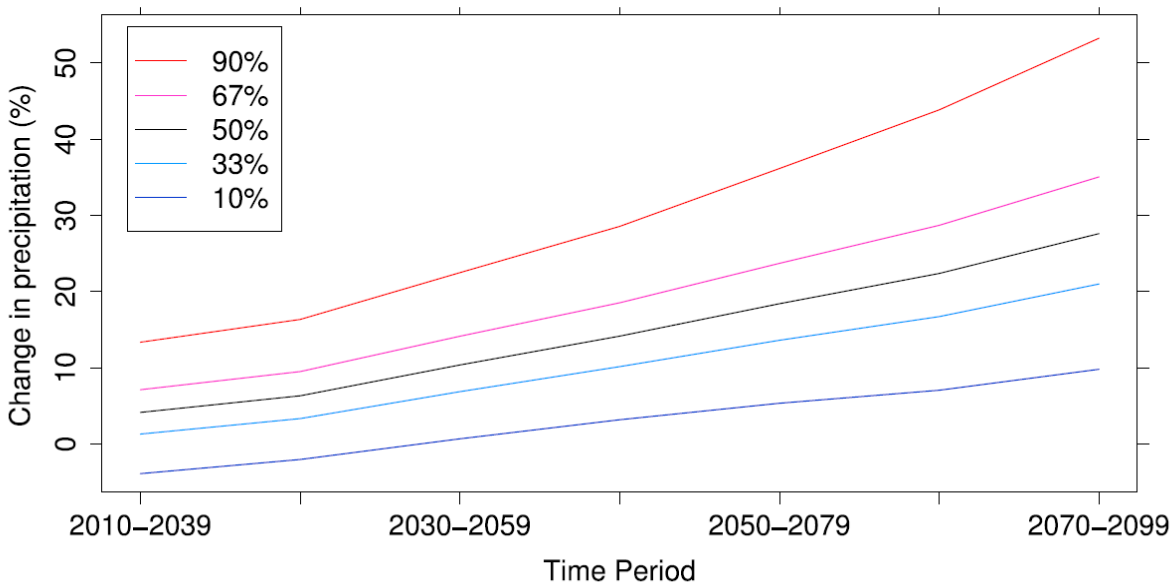


Figure B.9 – Plume plot of UKCP09 mean winter wettest day precipitation projections under High Emissions for the North West England River basin: 2020s to 2080s inclusive. © Crown copyright 2009

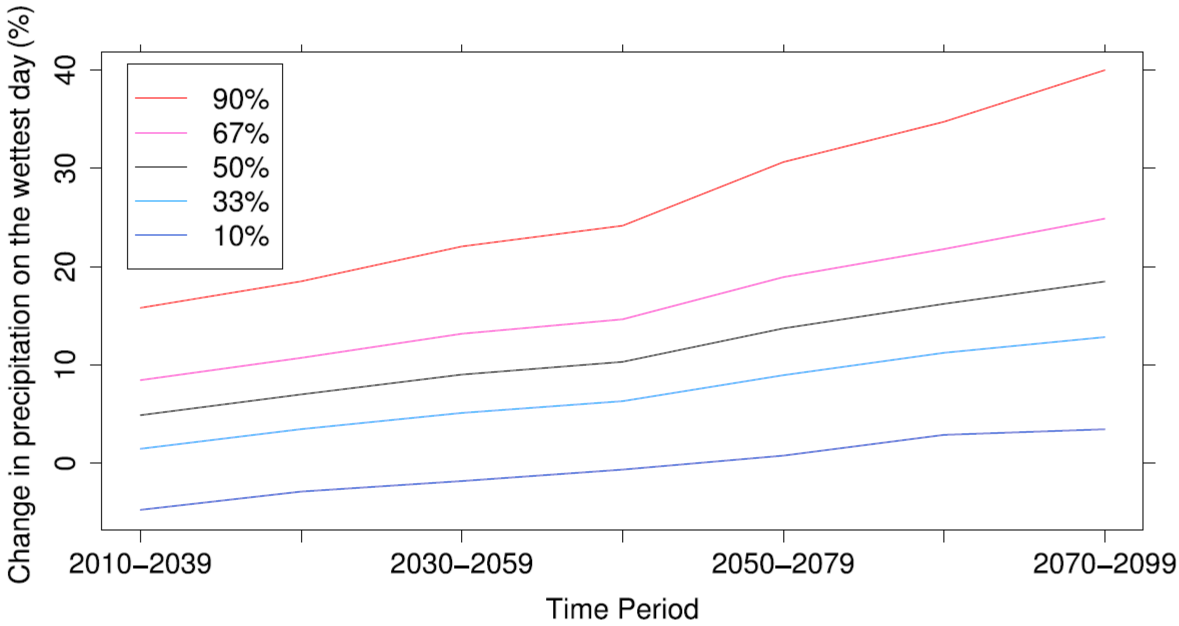


Figure B.10 – Plume plot of UKCP09 mean summer temperature projections under High Emissions for the North West England River basin: 2020s to 2080s inclusive. © Crown copyright 2009

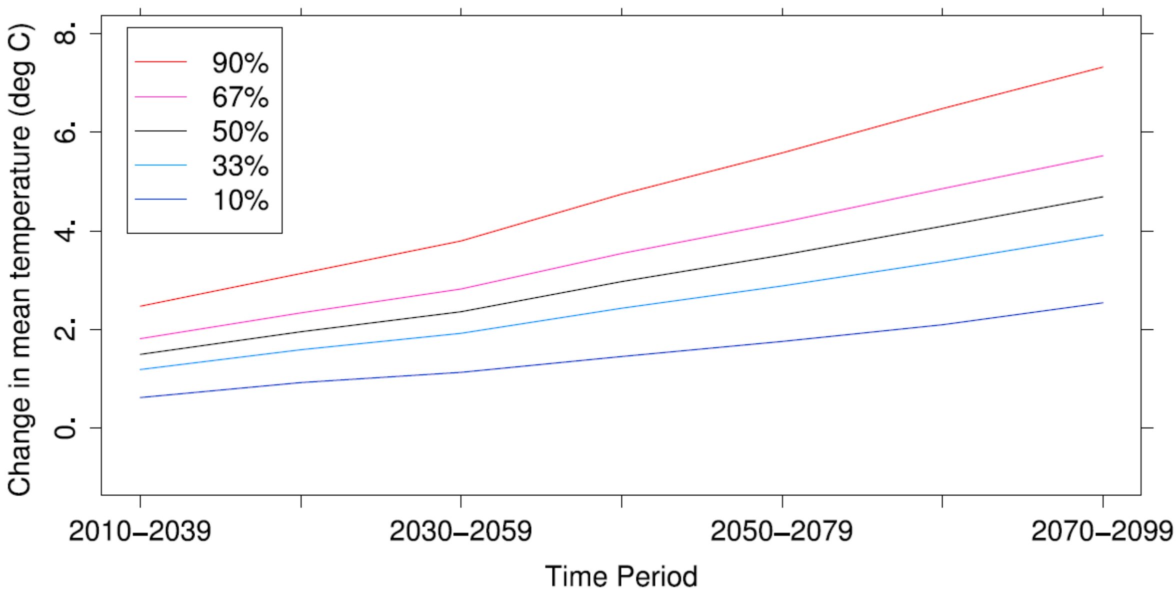


Figure B.11 – Plume plot of UKCP09 mean winter temperature projections under High Emissions for the North West England River basin: 2020s to 2080s inclusive. © Crown copyright 2009

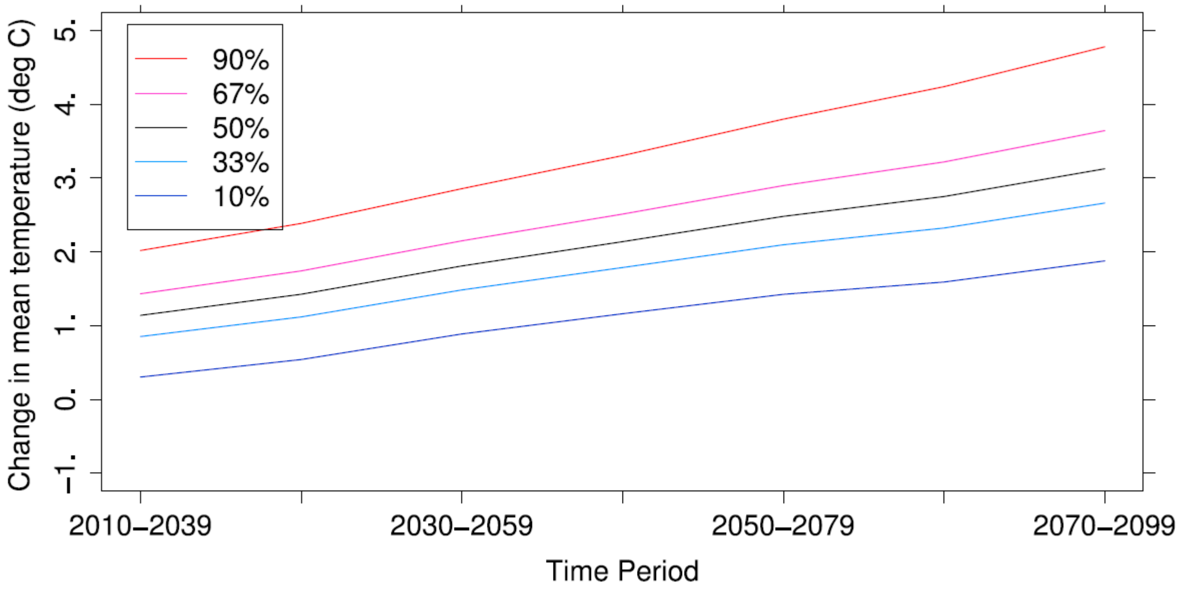
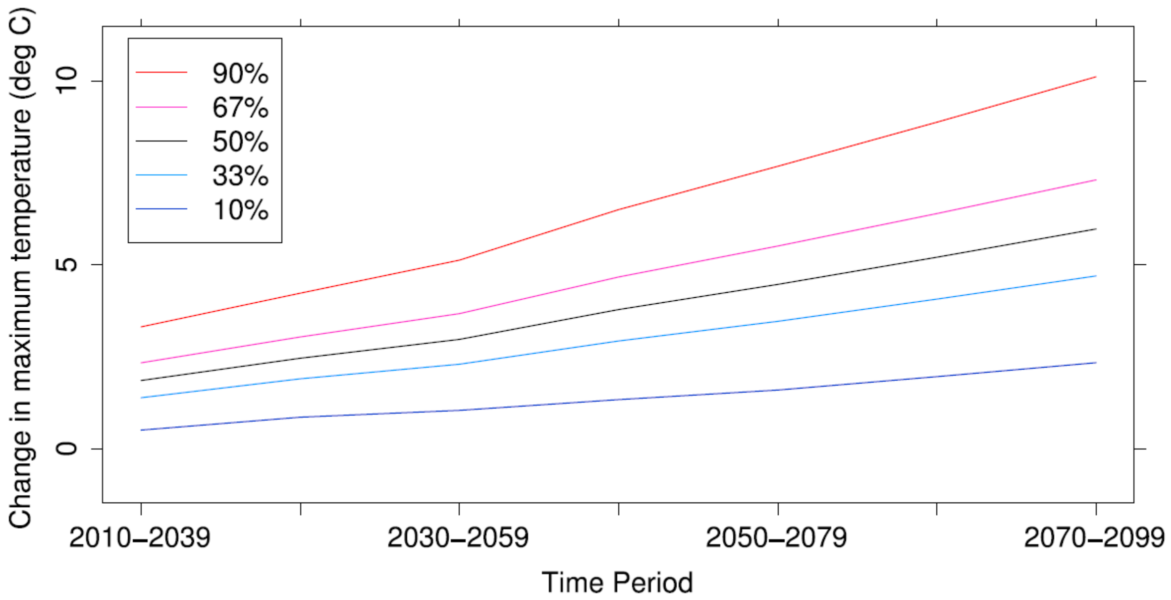


Figure B.12 – Plume plot of UKCP09 mean summer average daily maximum temperature projections under High Emissions for the North West England River basin: 2020s to 2080s inclusive. © Crown copyright 2009



B.3 Northumbria River Basin

Figure B.13 – Plume plot of UKCP09 mean summer precipitation projections under High Emissions for the Northumbria River basin: 2020s to 2080s inclusive. © Crown copyright 2009

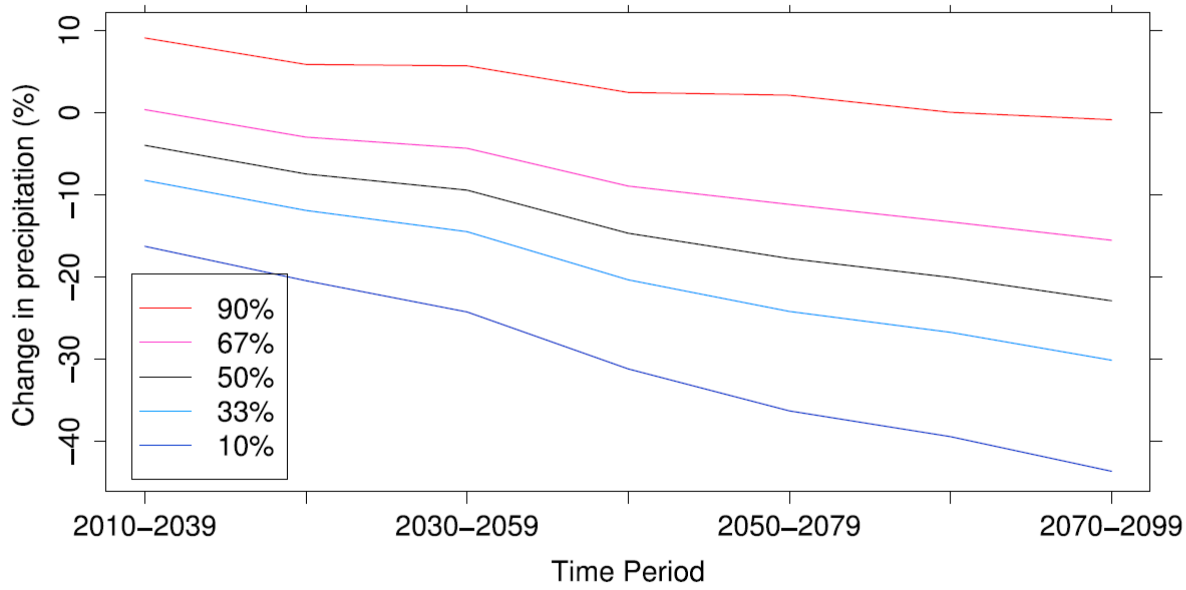


Figure B.14 – Plume plot of UKCP09 mean winter precipitation projections under High Emissions for the Northumbria River basin: 2020s to 2080s inclusive. © Crown copyright 2009

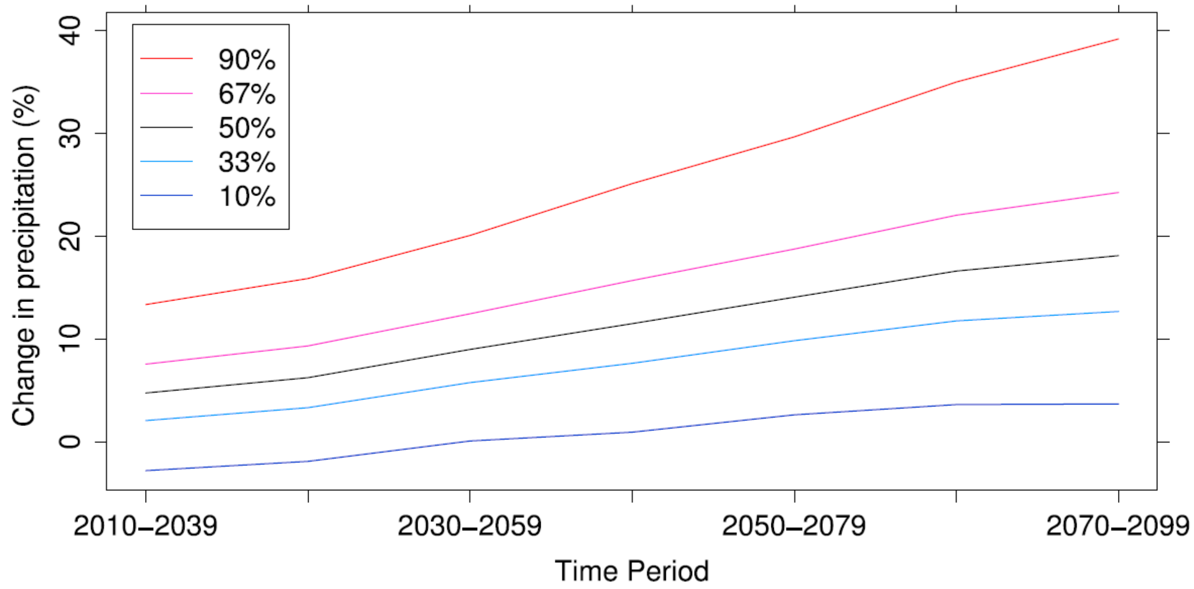


Figure B.15 – Plume plot of UKCP09 mean winter wettest day precipitation projections under High Emissions for the Northumbria River basin: 2020s to 2080s inclusive. © Crown copyright 2009

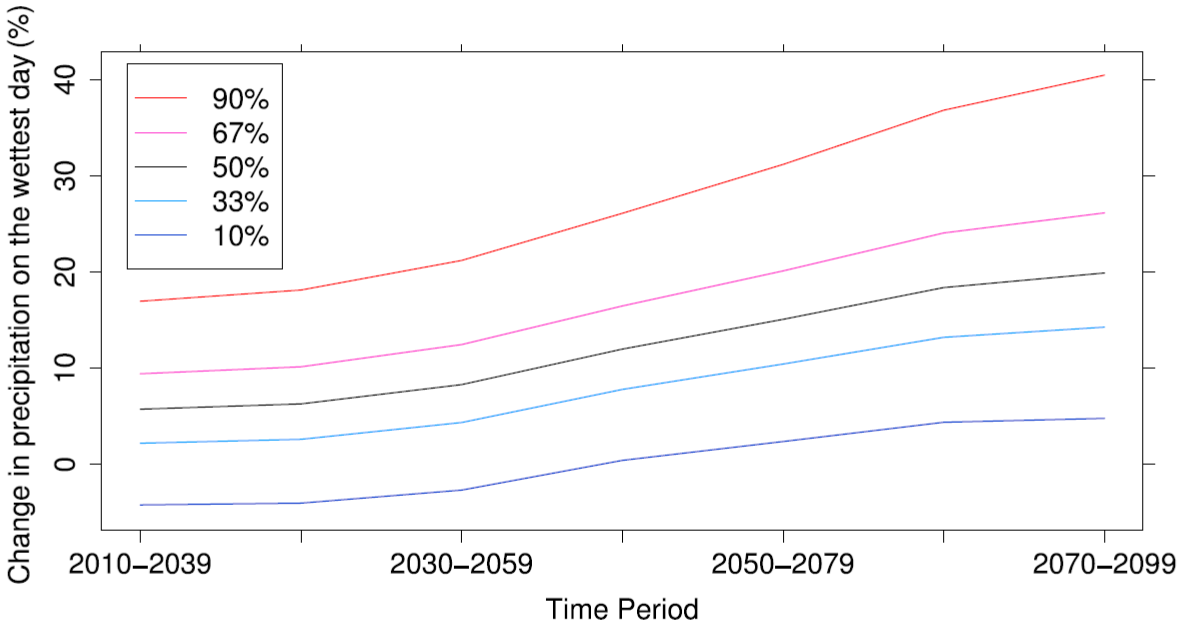


Figure B.16 – Plume plot of UKCP09 mean summer temperature projections under High Emissions for the Northumbria River basin: 2020s to 2080s inclusive. © Crown copyright 2009

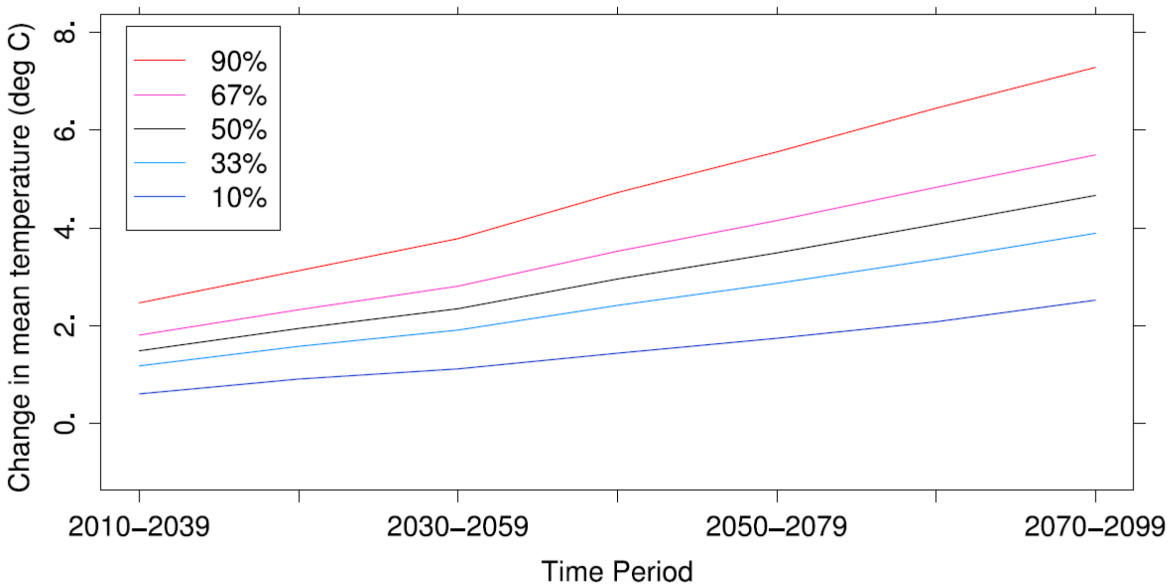


Figure B.17 – Plume plot of UKCP09 mean winter temperature projections under High Emissions for the Northumbria River basin: 2020s to 2080s inclusive. © Crown copyright 2009

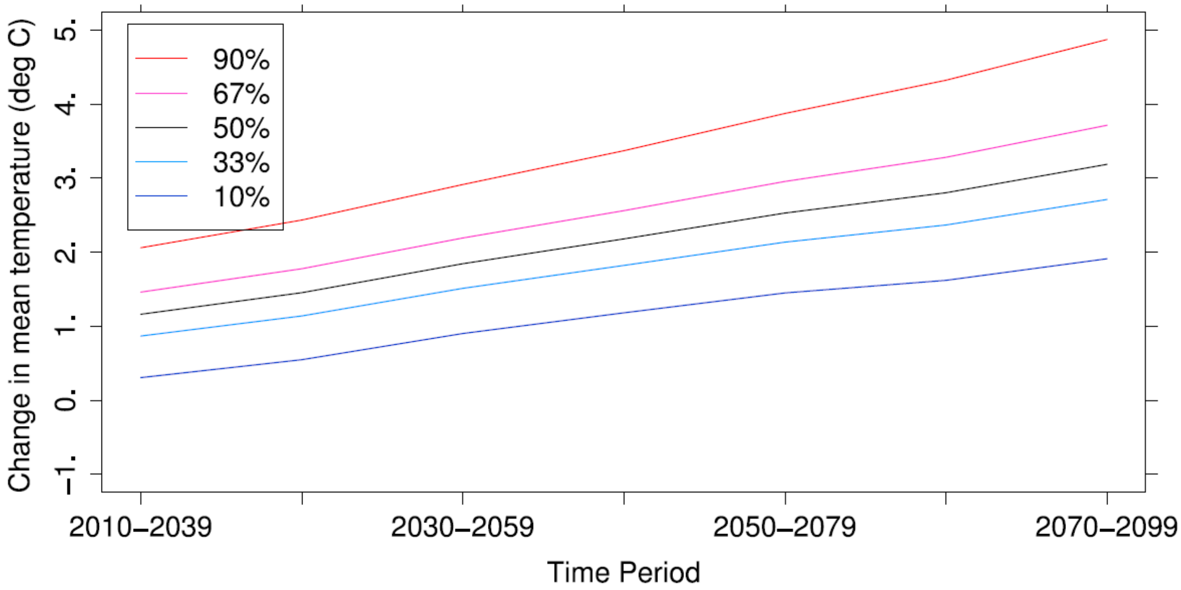
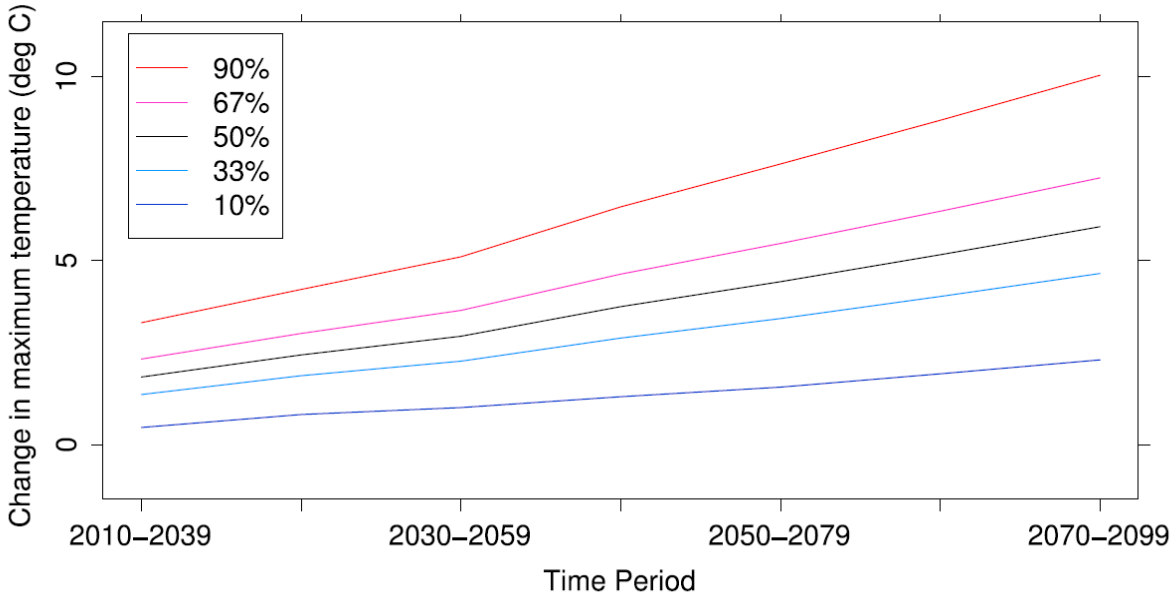


Figure B.18 – Plume plot of UKCP09 mean summer average daily maximum temperature projections under High Emissions for the Northumbria River basin: 2020s to 2080s inclusive. © Crown copyright



B.4 Severn River Basin

Figure B.19 – Plume plot of UKCP09 mean summer precipitation projections under High Emissions for the Severn River basin: 2020s to 2080s inclusive. © Crown copyright 2009

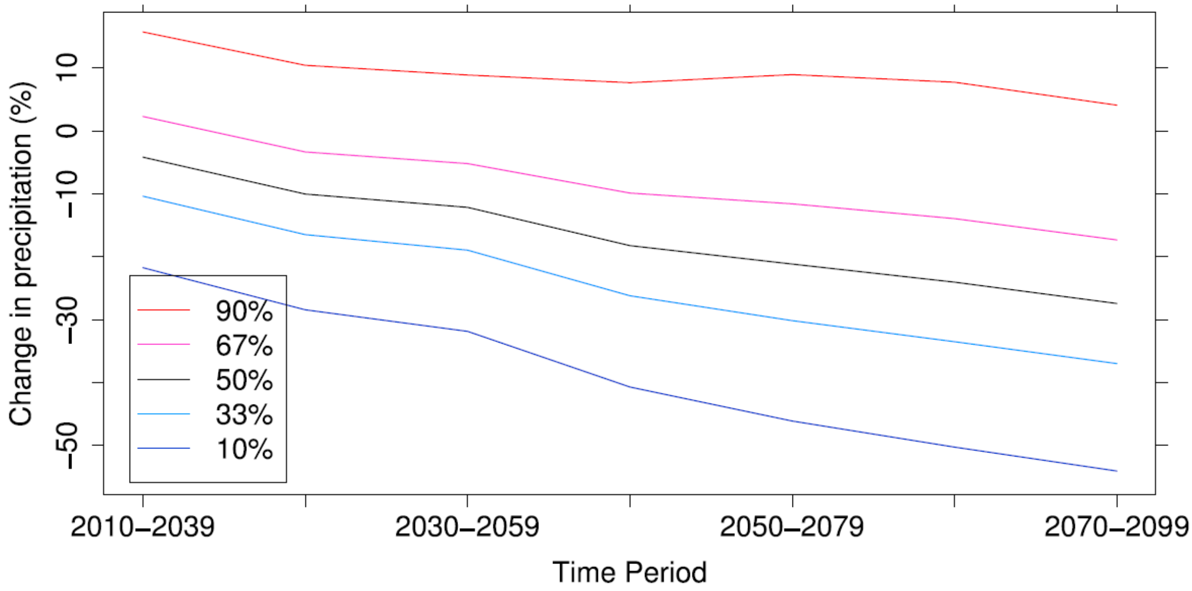


Figure B.20 – Plume plot of UKCP09 mean winter precipitation projections under High Emissions for the Severn River basin: 2020s to 2080s inclusive. © Crown copyright 2009

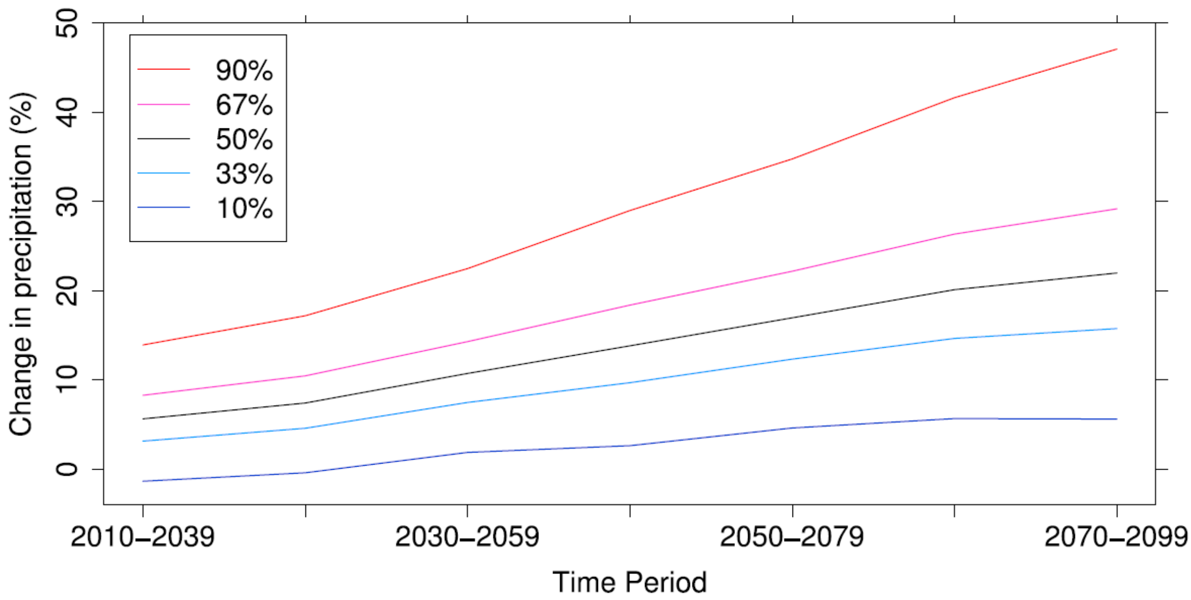


Figure B.21 – Plume plot of UKCP09 mean winter wettest day precipitation projections under High Emissions for the Severn River basin: 2020s to 2080s inclusive. © Crown copyright 2009

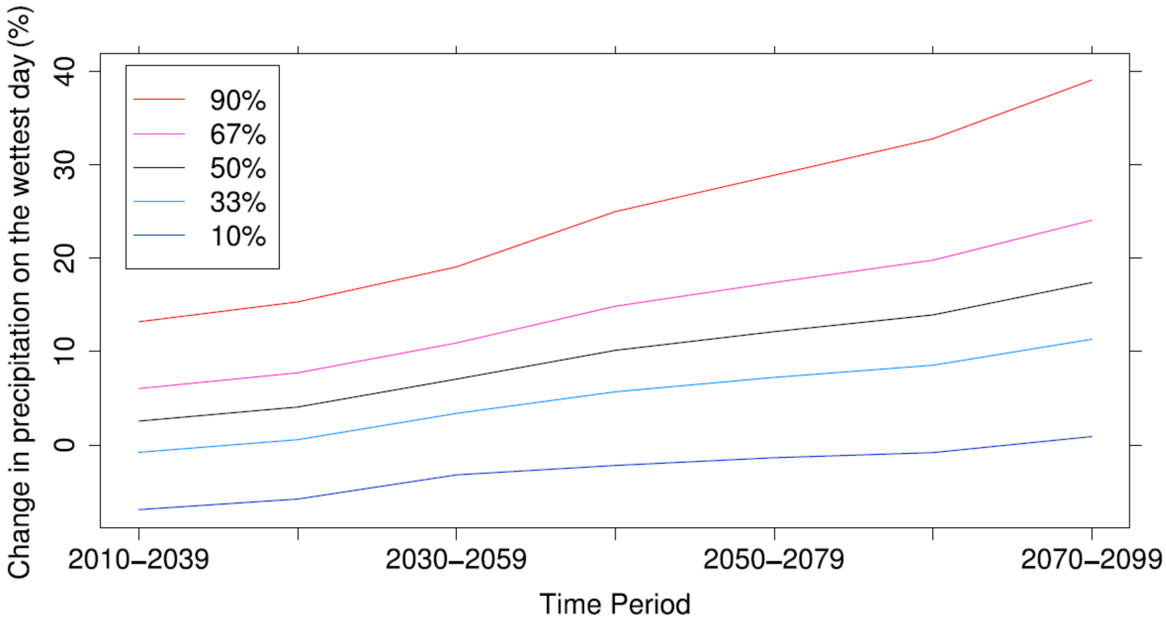


Figure B.22 – Plume plot of UKCP09 mean summer temperature projections under High Emissions for the Severn River basin: 2020s to 2080s inclusive. © Crown copyright 2009

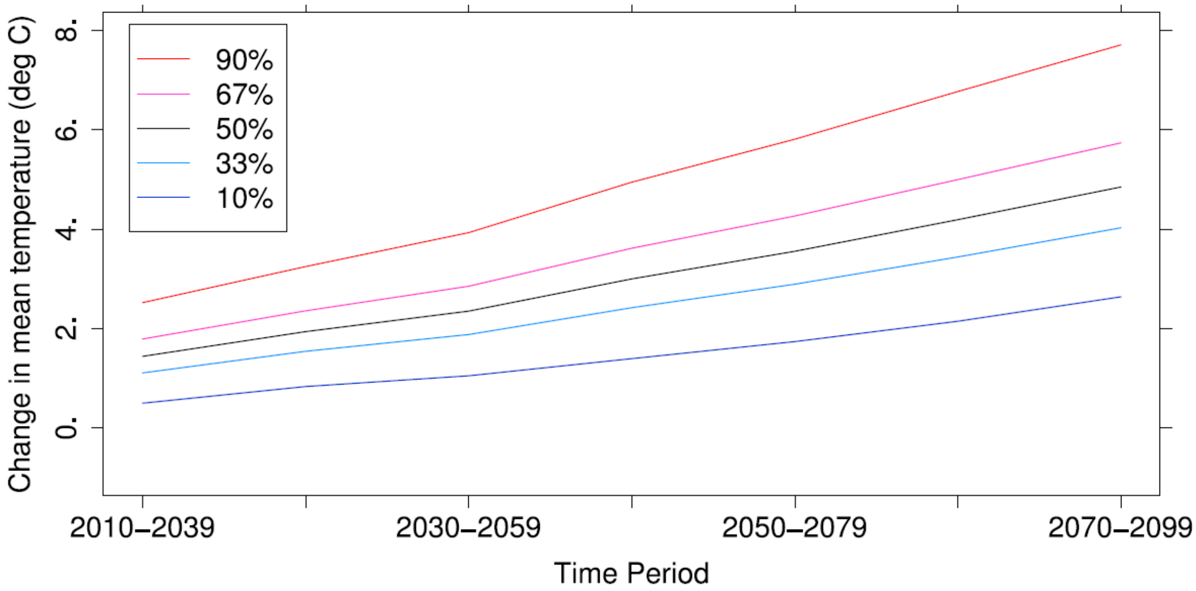


Figure B.23 – Plume plot of UKCP09 mean winter temperature projections under High Emissions for the Severn River basin: 2020s to 2080s inclusive. © Crown copyright 2009

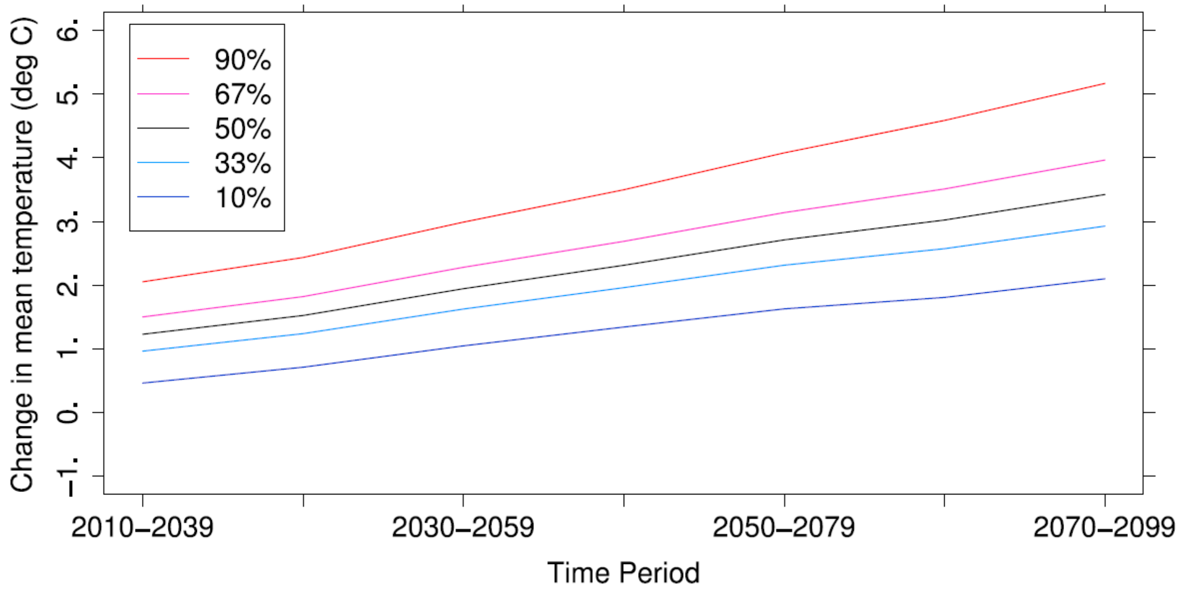
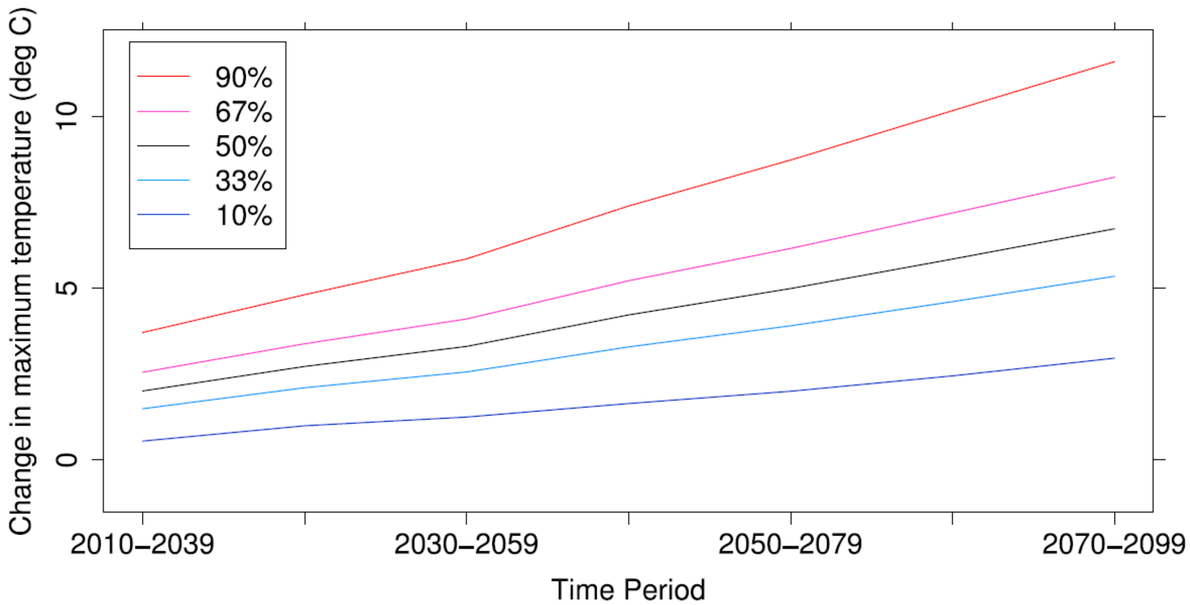


Figure B.24 – Plume plot of UKCP09 mean summer average daily maximum temperature projections under High Emissions for the Severn River basin: 2020s to 2080s inclusive. © Crown copyright 2009



B.5 South West River Basin

Figure B.25 – Plume plot of UKCP09 mean summer precipitation projections under High Emissions for the South West River basin: 2020s to 2080s inclusive. © Crown copyright 2009

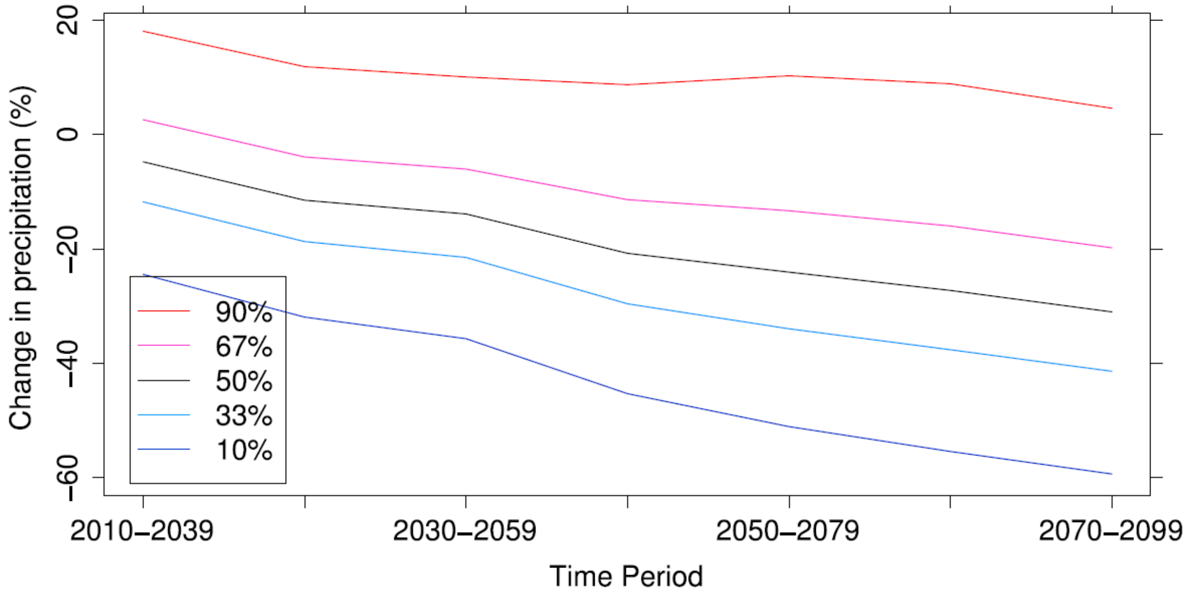


Figure B.26 – Plume plot of UKCP09 mean winter precipitation projections under High Emissions for the South West River basin: 2020s to 2080s inclusive. © Crown copyright 2009

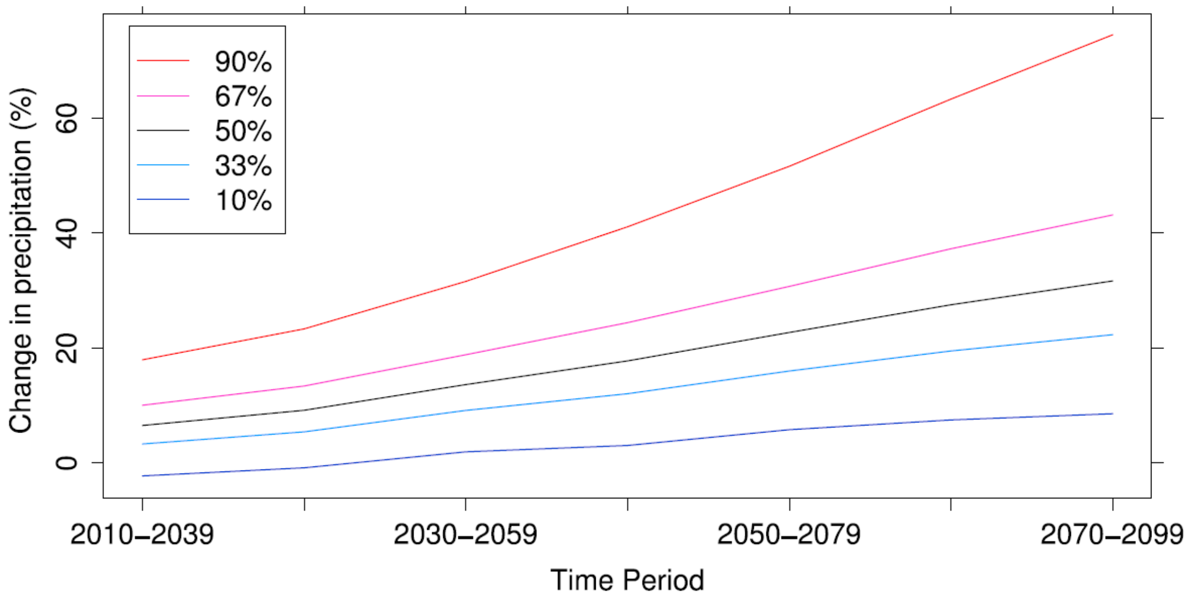


Figure B.27 – Plume plot of UKCP09 mean winter wettest day precipitation projections under High Emissions for the South West River basin: 2020s to 2080s inclusive. © Crown copyright 2009

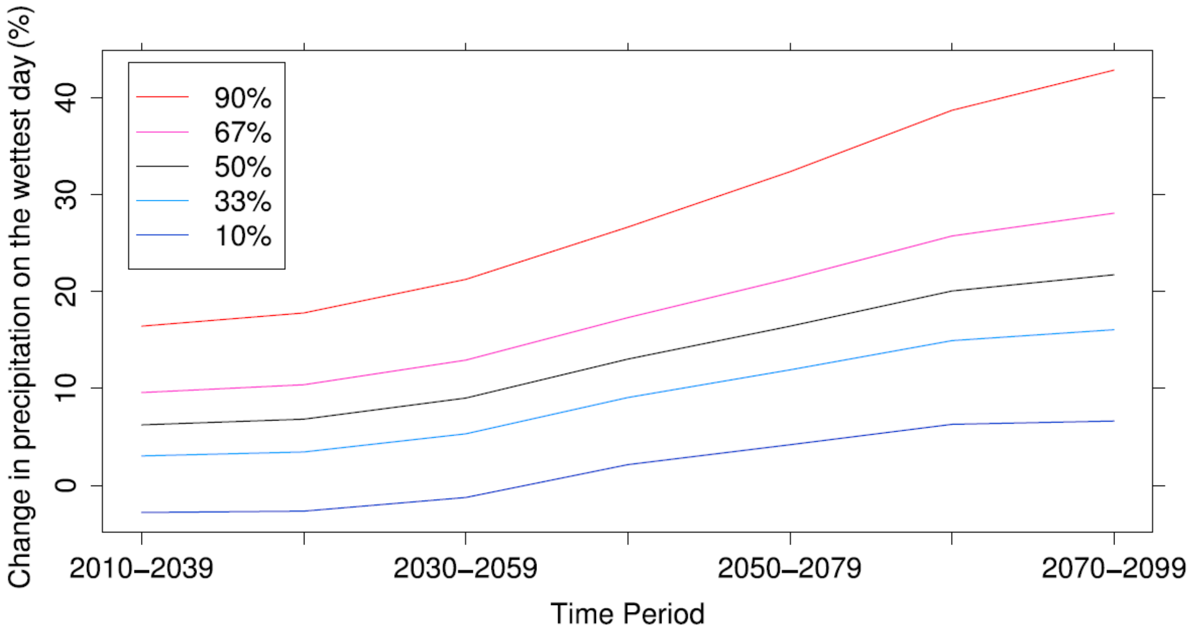


Figure B.28 – Plume plot of UKCP09 mean summer temperature projections under High Emissions for the South West River basin: 2020s to 2080s inclusive. © Crown copyright 2009

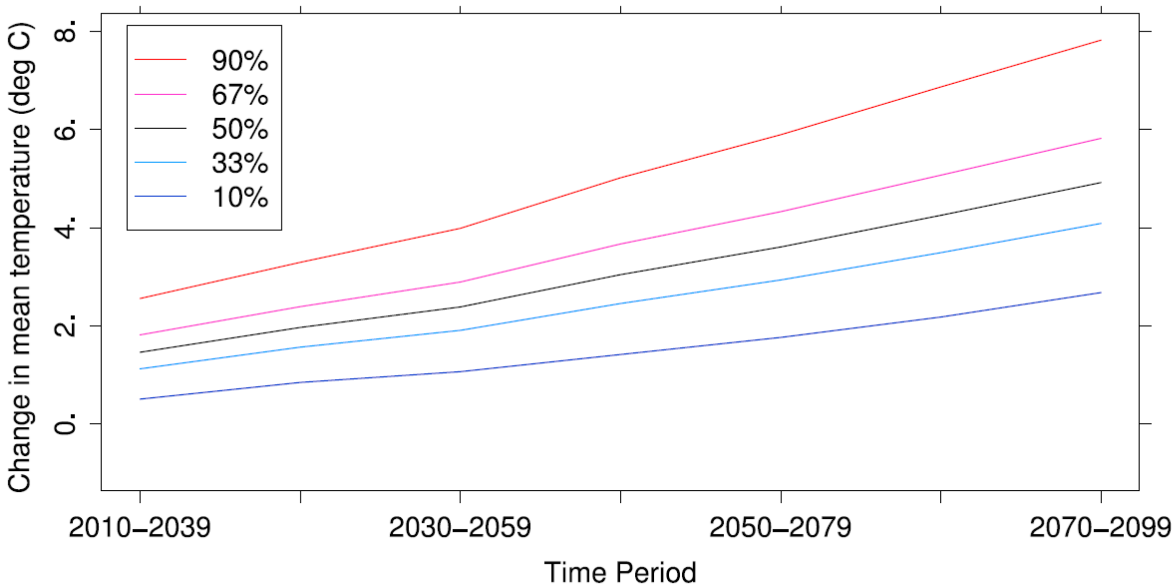


Figure B.29 – Plume plot of UKCP09 mean winter temperature projections under High Emissions for the South West River basin: 2020s to 2080s inclusive. © Crown copyright 2009

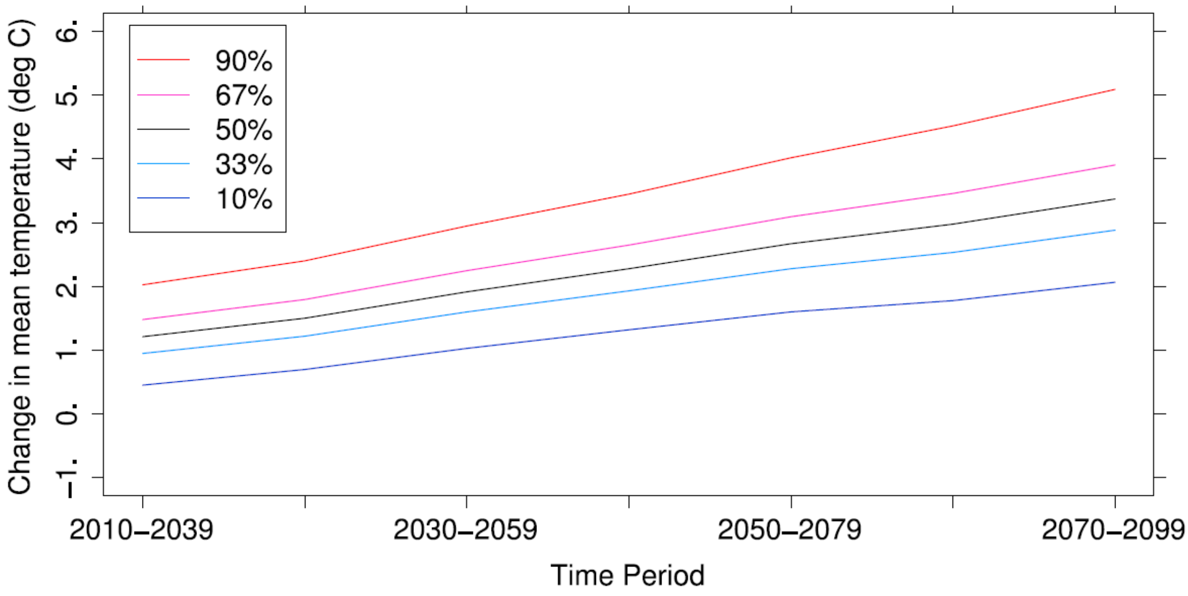
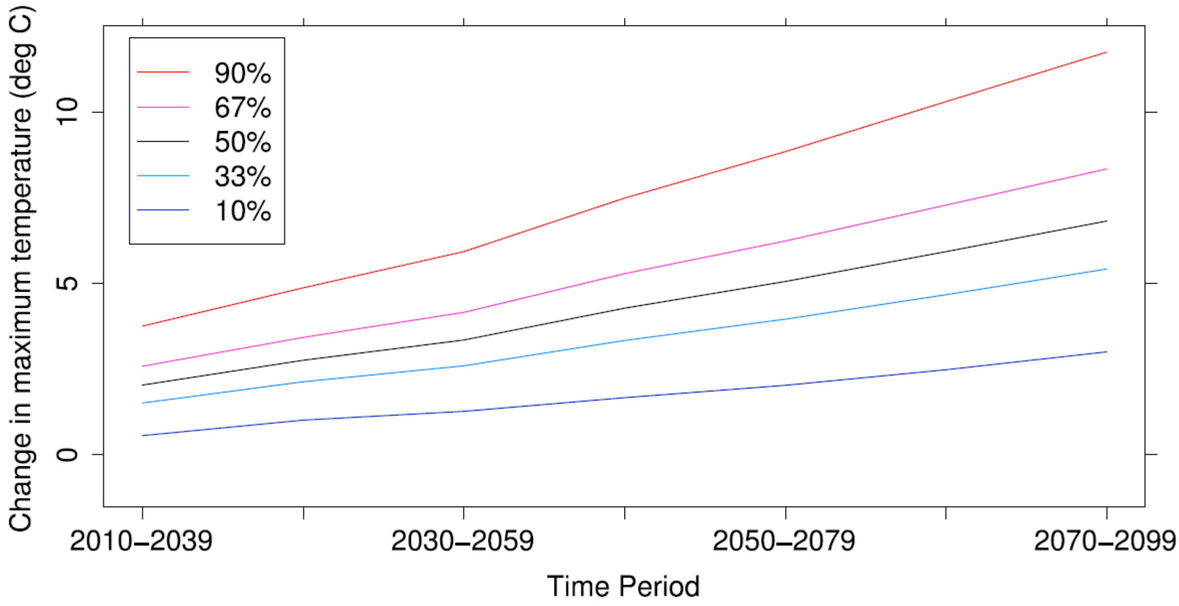


Figure B.30 – Plume plot of UKCP09 mean summer average daily maximum temperature projections under High Emissions for the South West River basin: 2020s to 2080s inclusive. © Crown copyright



B.6 Thames River Basin

Figure B.31 – Plume plot of UKCP09 mean summer precipitation projections under High Emissions for the Thames River basin: 2020s to 2080s inclusive. © Crown copyright 2009

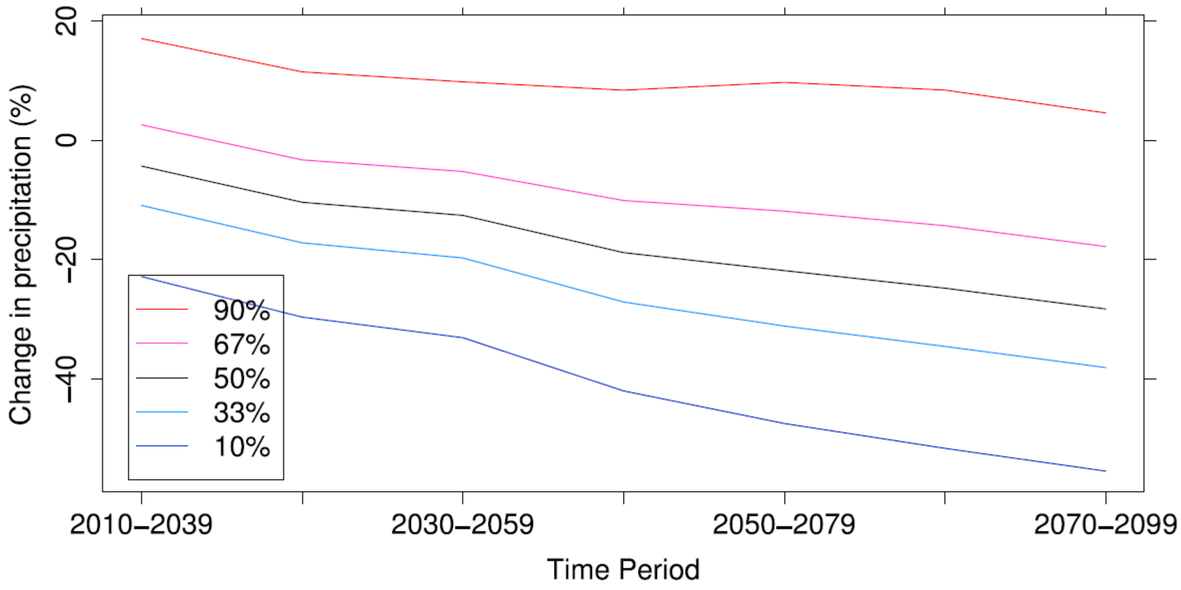


Figure B.32 – Plume plot of UKCP09 mean winter precipitation projections under High Emissions for the Thames River basin: 2020s to 2080s inclusive. © Crown copyright 2009

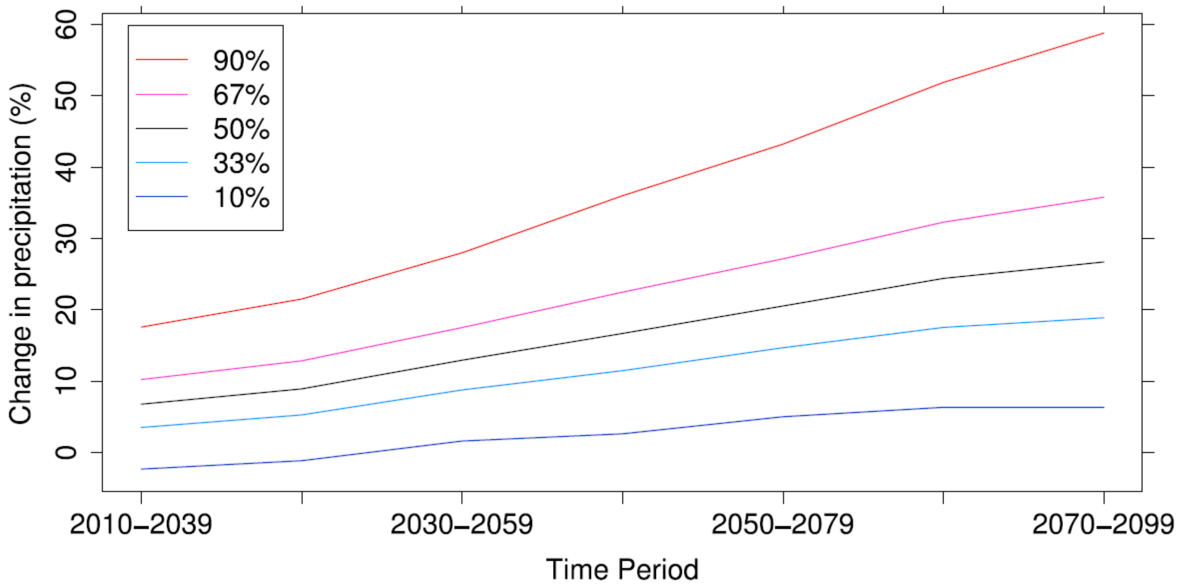


Figure B.33 – Plume plot of UKCP09 mean winter wettest day precipitation projections under High Emissions for the Thames River basin: 2020s to 2080s inclusive. © Crown copyright 2009

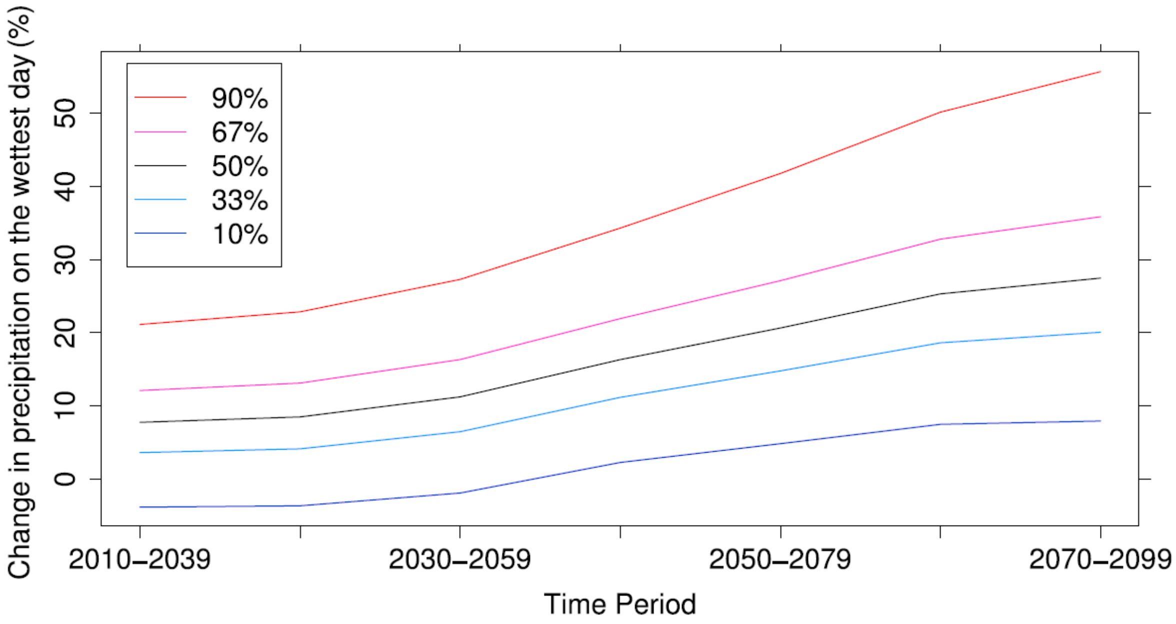


Figure B.34 – Plume plot of UKCP09 mean summer temperature projections under High Emissions for the Thames River basin: 2020s to 2080s inclusive. © Crown copyright 2009

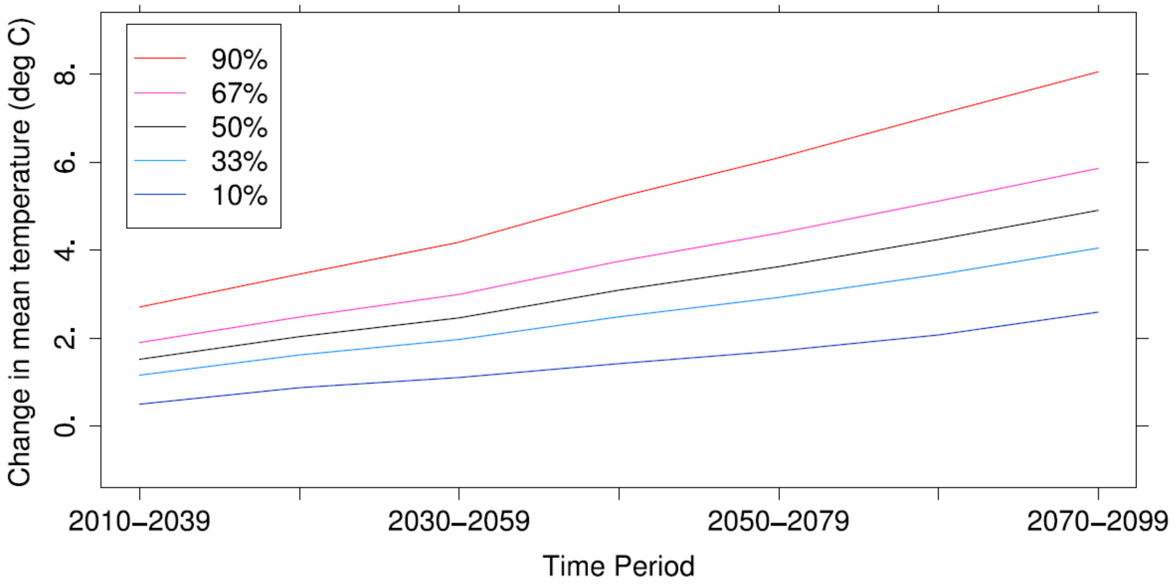


Figure B.35 – Plume plot of UKCP09 mean winter temperature projections under High Emissions for the Thames River basin: 2020s to 2080s inclusive. © Crown copyright 2009

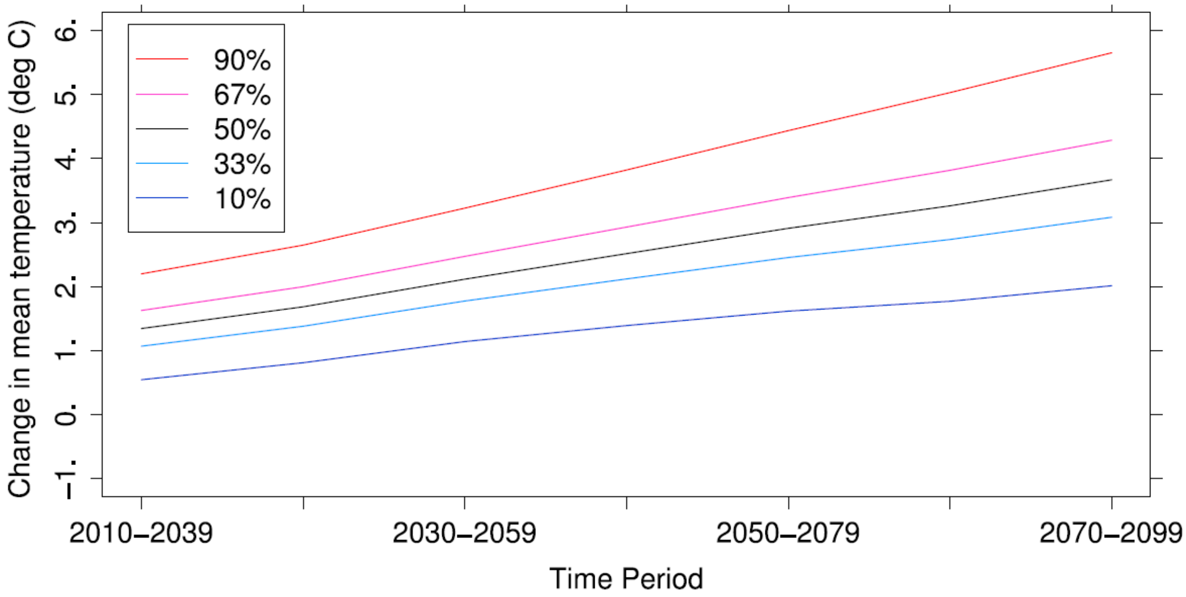
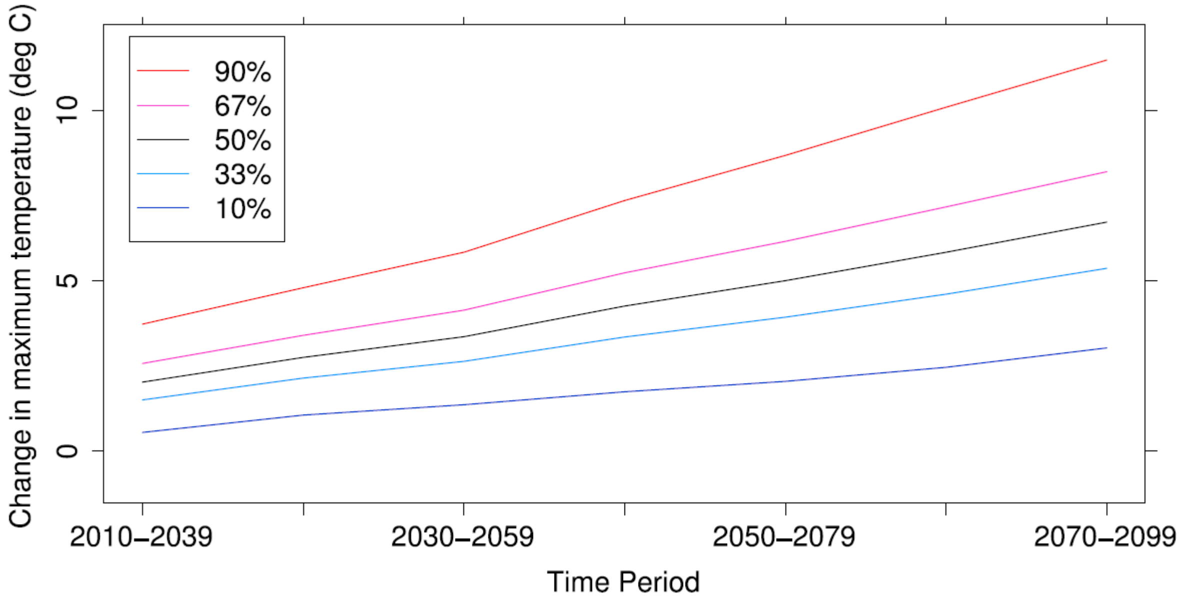


Figure B.36 – Plume plot of UKCP09 mean summer average daily maximum temperature projections under High Emissions for the Thames River basin: 2020s to 2080s inclusive. © Crown copyright 2009



Appendix C ‘Shortlist’ of potential vulnerabilities for function and form

Table C.1 - 'Short List' of potential vulnerability of reservoir function to climate change

Dam function	Climate variable	Potential impact	Potential exposure	Potential vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
Flood detention	High rainfall	Increased flow into reservoirs increases flood risk: increased storage requirements or less well managed floods.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall events also projected to increase in frequency and magnitude.	High	L	
		Increase in sedimentation during flood events could lead to reduction in flood storage capacity and/or blockage of spillways due to increased mobilisation of vegetation in flood flows.		Medium	P	Depends on existing rate of sedimentation and impact on storage. Need for quantification depends on the risk currently posed to the dam.
	High temperature	Increase in vegetation growth - potential reduction in reservoir capacity and/or blocking of spillways	Increase in summer temperature across the UK projected, heat wave conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increase in exposure to high temperature.	Medium	P	
Storage for seasonal use	High rainfall	High rainfall events leading to increased peak flows into impounding reservoirs can lead to overtopping. Dams may need to be operated at lower or more variable levels to mitigate against this risk, potentially reducing available storage.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall events also projected to increase in frequency and magnitude.	High	L	
		Increase in sedimentation during flood events could lead to a reduction in water storage capacity.		Medium	P	Depends on existing rate of sedimentation and impact on storage. Need for quantification depends on the risk currently posed to the dam.

Dam function	Climate variable	Potential impact	Potential exposure	Potential vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
		Increase in turbidity during flood events could leading to water clarity & quality issues with resultant increased treatment requirements. Water may no longer be suitable for some uses at certain times of year		Medium	P	Depends on existing water quality and significance of high flows/rainfall events on turbidity (include treatment capacity in assessment). Only quantify for sources identified as being currently vulnerable to turbidity issues
	Low rainfall	Lower rainfall will lead to lower flows, decreasing reservoir levels and less water will be available for use. Reduced yields.	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	High	L	Already carried out as part of the WRMP process for undertakers in England & Wales
		Low rainfall will increase demand for water for irrigation and environmental uses.		High	L	Already carried out as part of the WRMP process for undertakers in England & Wales
		For reservoirs with secondary purposes, management conflicts can occur when draw down is required for primary function (e.g. recreational use of water supply reservoirs; environmental flow releases).		High	L	Already carried out as part of the WRMP process for undertakers in England & Wales
		Lower water levels leading to increased concentration of pollutants, lower water quality and higher treatment requirements		High	L	Large variability and difficult to link to climatic factors. Risk based approach under uncertainty recommended
	High temperature	Increase in water temperature leading to increased vegetation growth and eutrophic conditions. Increased duration and frequency of Algal blooms. Reduction in water quality and increase in treatment requirements. Water may not be suitable for some purposes (e.g. environmental releases).	Increase in exposure as summer temperatures projected to increase. What is currently considered extreme could become the norm. Extreme heat waves are also likely to increase in frequency and magnitude.	High	L	Quantification of vegetation and algal responses is almost impossible. Risk based approach needed.

Dam function	Climate variable	Potential impact	Potential exposure	Potential vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
		Increase in evaporation of stored water, and transpiration from vegetation and soils - lower water levels in reservoirs and less available for use.		Medium	P	Quantification will be needed where reservoir output is the key function. Otherwise risk based approach should be sufficient.
Recreation and aesthetic	High rainfall	Increased sedimentation and debris during and following flood events - impact on recreational safety, turbidity and aesthetic value.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall events also projected to increase in frequency and magnitude.	Medium	P	
		Increased flows resulting in overtopping of reservoirs. For recreation and aesthetic function, impacts on downstream navigation, downstream water users (caneoists etc).		High	L	
	Low rainfall	Drawdown exposing littoral habitat - impact on biodiversity and loss of aesthetic value.	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	Medium	P	
		Low water levels may prevent certain types of recreation e.g. sailing, or cause access difficulties.		High	L	Only need to quantify if risk based assessment first shows that this could be an issue
		Lower water levels leading to increased concentration of pollutants and lower water quality may reduce aesthetic value and biodiversity. May create health issues if severe		High	L	Only likely to be significant if poor water quality already exists. Use risk based approach first to determine if quantification is needed.
	High temperature	Increase in pests e.g. midges; consider issues associated with mosquitoes and disease in the south	Increase in exposure as summer temperatures projected to increase. What is currently considered extreme could become the norm. Extreme heat waves are also likely to increase in frequency and magnitude.	Medium	P	Very uncertain risk. 'Watch and monitor' approach recommended
		Increase in visitor numbers in shoulder season - extended recreation and tourism season		Medium	P	Quantification may be required if peak visitors are likely to be a problem. Would need to relate visitor numbers to temperature.

Dam function	Climate variable	Potential impact	Potential exposure	Potential vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
		Increase in vegetation growth - potential impact on aesthetic value and recreation potential		Medium	P	Quantification of vegetation responses is almost impossible. Risk based approach needed.
		Increase in frequency of algal blooms - blue green algae can be harmful to human health		High	L	Quantification of algal responses is almost impossible. Risk based approach needed.
		Increased vegetation growth leading to navigation problems for some craft.		Medium	P	As above
Electricity generation	High rainfall	Damage caused to HEP auxiliary infrastructure (power houses etc) by flooding could be very costly - damage to assets and electricity supply outage.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall events also projected to increase in frequency and magnitude.	High	L	Link hydrological/reservoir models to UKCP rainfall increases
		Flood risk may require reduced operating levels, reducing availability or flexibility of power generation.		High	L	As above; use water balance models to evaluate impacts on use/storage if risk reduction is used.
		Increase in water available for release during winter		High	L	As above, but possible benefit
	Low rainfall	Decrease in water available for release/flush during summer	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	High	L	Link hydrological and water balance models to UKCP09 scenarios - evaluate impact on water available.
	High temperature	Change in demand for electricity – milder winters reduce power demand, hotter summers increased demand. Opposite to seasonal water availability.	Increase in exposure as summer temperatures projected to increase. What is currently considered extreme could become the norm. Extreme heat waves are also likely to increase in frequency and magnitude.	Medium	L	Demand modelling may be needed for larger reservoirs

Dam function	Climate variable	Potential impact	Potential exposure	Potential vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
Effluent	High rainfall	Increased flow into impounding reservoirs increases flood risk and risk of overtopping with the resultant downstream pollution risk. Also may require lower operating levels.	Potential for increasing exposure as mean rainfall increases. What is considered extreme currently could become the norm. Extreme rainfall events are also projected to increase in frequency and magnitude.	High	L	Quantified risk modelling based on UKCP09 likely to be required unless significant spare capacity is available.
	Low rainfall	For impounding reservoirs will result in lower fresh water inflows leading to increased concentration of pollutants and lower water quality.	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	High	L	Mass balance modelling using hydrological factors may be necessary
		Lower river flows may reduce ability to abstract from and discharge to the environment.		Medium	P	Quantification by dam owners unlikely to be required; Environment Agency will be responsible for reviewing consents as threats to water courses become apparent.
	High Temperature	Increased receiving water temperatures may reduce capacity of environment to accept effluent discharge and may affect ability to treat discharges		High	P	Quantification by dam owners unlikely to be required; Environment Agency will be responsible for reviewing consents as threats to water courses become apparent.

Table C.2 - 'Short List' of potential and current vulnerability of climate change to reservoir function

Dam form		Climate variable	Potential impact	Potential exposure	Future vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
Erodible	Clay core & homogenous clay construction	High rainfall	More rapid fluctuations in operating water levels possibly leading to net increases in pore pressure. This includes rapid fill or emptying (as an operational response) in advance of heavy rains. Risk of piping failure or mass instability as a result.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall events also projected to increase in frequency and magnitude.	Medium	P	Only quantify in unusual conditions where this is considered to be a potential risk. Difficult to model piping failure because of highly site specific nature.
			Water levels above design levels results in a risk of overtopping and erosion of the downstream face.		High	L	If there is a significant risk, then hydrological modelling required to determine likelihood
			Direct rainfall may cause erosion of dam face (normally downstream)		High	L	Quantification unlikely to be needed - risk based approach and monitoring are appropriate
			Higher water levels may lead to an increase in seepage (flow paths may exit higher up on downstream face)		High	L	
			For reservoirs sited in floodplains, elevated flood risk may lead to greater erosion and damage to reservoir toe. Long-term repeated, seasonal exposure to flooding could reduce reservoir toe integrity		Medium	P	Quantify increase in flood risk if this is a critical risk item, or if EA flood mapping is updated
		Low rainfall	Desiccation and shrinkage of clay core and dam shoulders.	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	High	L	Risk to dam largely depends on length of exposure. Anticipated changes to water levels will need reviewing - see Function: Seasonal storage for comments
			Loss of vegetation cover, increasing the risk of cracking and reducing surface erosion protection		High	L	Not possible to quantify - risk based approach needed
			May result in lower water levels, exposing unprotected sections of the dam face to erosion.		High	L	Quantification of water levels should be used where models are available. Use risk based evaluation based on increased exposure times

Dam form		Climate variable	Potential impact	Potential exposure	Future vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
			Decreases in summer rainfall can lead to more pronounced, more regular cycles of dam wetting and drying, potentially leading to slumping of the upstream dam face.		Medium	P	Would be captured in assessment of high and low levels described above
		High Temperature	Increased evapotranspiration contributing to desiccation and shrinking of clay	Increase in summer temperature across the UK projected, heat wave conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increase in exposure to high temperature.	High	P	Depend on topsoil – unlikely if good topsoil cover
			Increased vegetation growth on dam face, if co-incident with increased rainfall. Increased maintenance requirements.		Medium	P	Not possible to model. Qualitative risk assessment only
Erodible	HDPE liner	High rainfall	Water levels above design levels results in a risk of overtopping and erosion of the downstream face.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall events also projected to increase in frequency and magnitude.	High	L	Use UKCP09 factors in existing hydrological models for the dam
		High temperature	HDPE is vulnerable to UV light; it leads to more rapid degradation of the material. High evaporation rates arising from high temperatures may lead to low water levels and increased exposure of liners to sunlight.	Increase in summer temperature across the UK projected, heat wave conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increase in exposure to high temperature.	Medium	P	Not realistic to model; used risk based approach

Dam form		Climate variable	Potential impact	Potential exposure	Future vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
		Low rainfall	Low water levels and hence exposure of HDPE liner to sunlight	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	Medium	P	Not as critical as clay core. Use water balance models to examine exposure if available elsewhere, otherwise risk based approach is adequate
		Wind	Wind can lift liners if there is no overburden in place. Causes slumping and mass instability.	Projections are uncertain.	Medium	P	Risk based approach sufficient
	Concrete liner	Low rainfall	Low water levels can lead to exposure of liner, increasing susceptibility to thermal cracking	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	Medium	P	Only needs quantifying in cases with existing, known issues
		High temperature	Increase in thermal cracking and spalling of concrete liner	Increase in summer temperature across the UK projected, heat wave conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increase in exposure to high temperature.	Medium	P	Risk based, engineering assessment of potential temperature impacts
			UV damage to concrete & joint materials.		Medium	P	Risk based, engineering assessment of potential temperature impacts

Dam form		Climate variable	Potential impact	Potential exposure	Future vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
	Asphaltic concrete	High rainfall	When co-incident with wind can result in wave action at higher levels on liner and dam.	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	Medium	P	
		Low rainfall	Low water levels can lead to exposure of liner, increasing susceptibility to block cracking	Decrease in summer rainfall projected across the UK, drought conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increases in exposure to low rainfall.	Medium	P	Water resource/mass balance models carried out for other purposes could be used to analyse exposure times. However, specific quantification of this issue is unlikely to be necessary
		High temperature	Increase in block cracking of liner if asphalt dries out. May resulting in slumping and mass instability.	Increase in summer temperature across the UK projected, heat wave conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increase in exposure to high temperature.	High	L	Risk based, engineering assessment of potential temperature impacts likely to be sufficient, although modelling of water level impacts may be necessary if there is a particular risk at a particular site
			Increased temperatures may result in reduced performance of current asphaltic binding mixes		Medium	P	Risk based, engineering assessment of potential temperature impacts
			Diurnal temperature variations can lead to longitudinal cracking.		Medium	P	Risk based, engineering assessment of potential temperature impacts
Non-erodible	Masonry, concrete	High rainfall	Water levels above design levels results in a risk of overtopping.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall	Medium	P	Hydrological modelling should be carried out for higher risk structures; combine with UKCP09 scenarios

Dam form		Climate variable	Potential impact	Potential exposure	Future vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
			Water levels above design levels result in risks of sliding and overturning.	events also projected to increase in frequency and magnitude.	Medium	P	Unlikely to be a significant mechanism
		High temperature	Thermal expansion resulting in cracking and spalling.	Increase in summer temperature across the UK projected, heat wave conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increase in exposure to high temperature.	Medium	P	Risk based, engineering assessment of potential temperature impacts
			UV damage to concrete & masonry/jointing materials.		Medium	P	Risk based, engineering assessment of potential temperature impacts
All	Spillways	High rainfall	High flows and water levels exceeding spillway designs can result in spillway failure.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall events also projected to increase in frequency and magnitude.	High	L	Hydrological modelling should be carried out based on UKCP09 forecasts
			High rainfall hence flows may increase transport of debris, potentially damaging or blocking spillway.		Medium	P	Not realistic to try and model; extrapolate from known risks in catchment
		High temperature	Possible cracking of concrete spillways during heat waves	Increase in summer temperature across the UK projected, heat wave conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increase in exposure to high temperature.	High	L	Asset deterioration assessment/modelling should be considered for high risk structures. Consider construction and makeup of reinforcement and potential for differential expansion

Dam form		Climate variable	Potential impact	Potential exposure	Future vulnerability	Significant? L= likely, P = possibly	Notes on Significance and Potential Quantification
	Auxiliary structures	High rainfall	High rainfall hence flows may increase transport of debris, potentially damaging dam components.	Potential for increasing exposure as mean rainfall increases. Events currently considered extreme could become the norm. Extreme rainfall events also projected to increase in frequency and magnitude.	Medium	P	Not realistic to try and model; extrapolate from known risks in catchment
		High temperature	Possible cracking of concrete channels and wave walls.	Increase in summer temperature across the UK projected, heat wave conditions could become more common and events currently considered extreme could become normal summer conditions. Likely to see increase in exposure to high temperature.	Medium	P	Lower risk; engineering risk assessment of asset failure modes and monitoring should suffice
			Expansion of metal elements (e.g. steel lining of tunnels, bottom outlet valves) in excess of design tolerances		Medium	P	Lower risk; engineering risk assessment of asset failure modes and monitoring should suffice

Appendix D Case Studies

D.1 Case Study 1

Background

The main study subject was a large, largely offline storage reservoir that is used primarily for public water supply purposes in the south of England. The study involved an interview with the Supervising Engineer, who also provided information about potential climate change impacts for a number of other water supply dams in southern England; this case study therefore effectively covers a number of water supply reservoirs with similar forms and functions.

Dam form and function

Form

The dam structure for primary study is formed of a clay core earthfill embankment with concrete wavewall and concrete slab revetments to the upstream face. The downstream face is grassed and there is a hard standing access road across the crest of the embankment. The structure includes an under-drainage blanket with a grout curtain cutoff wall sited beneath the upstream side of the embankment. There are a number of French drains on the downstream face to control surface runoff. Under-drainage is measured by means of a number of v-notch weirs.

The draw off and spillway are situated within the same structure and pass through the embankment by means of a twin bore tunnel. Water supply from the draw off runs to a number of sources, including another raw water reservoir, and there is a facility for discharge to the river as part of a flow augmentation scheme. There is a reinforced concrete chute that transfers spillway water and augmentation discharges to the downstream river.

Function

Reservoir refill relies primarily on pumped abstraction and takes water from a number of different sources. There is a catchment that feeds directly into the reservoir, but this is very small in comparison to the pumped refill. Refill and reservoir levels are dictated by operational issues outside of drought periods, and there is a control curve in place for drought operation.

The reservoir is used extensively for recreational purposes including sailing, fishing (shoreline and boat), walking and cycling. A significant proportion of the land and a number of the recreational buildings have been leased to a private operator who runs the sailing and fishing activities as a commercial enterprise.

Management and inspection regime

In terms of safety and maintenance (i.e. form), the water undertaker carries out routine monitoring of piezometers and has term contracts in place for maintenance and surveying. For formal reporting under the Reservoir Act 1975, visits are carried out by an appointed Supervising Engineer every 6 months followed by Statements and the last Inspecting Engineer’s report maintained a 10 yearly inspection period. Maintenance issues are raised as suggestions within the Supervising Engineer Statements and are included within the normal water industry AMP expenditure cycle. Communication channels are good, there are well established relationships between the Water Undertaker, the Supervising Engineer and the Inspecting Engineer, and there is a well established regulatory process that ensures funding can be made available as required. Referral from the Supervising Engineer to the Inspecting Engineer may sometimes be required if there are safety critical items that need to be escalated within the budgeting process. It was noted that maintenance suggestions made by the Supervising Engineer may become mandatory once the new Flood and Water Management Act (2010) comes into force; this will be discussed as part of the main guidance for this project.

In terms of function, the management regime is more complicated. Water supply is the over-riding functional purpose, and drought operation and potential yield are evaluated strategically by the Water Undertaker as part of the Water Resources Management Plan process. The strategic evaluation relies on a combination of hydrological and water resource planning models which reflect the complicated environmental abstraction and release constraints that dictate refill capacity. Day to day operation outside of drought periods is managed by operational staff. Management of fisheries and sailing is carried out by the private operators and liaison with the water undertaker tends to be informal. The leases that are in place do not require the water undertaker to allow for fisheries, sailing or other recreational requirements when considering how and where water is abstracted from the reservoir or how quickly water levels are raised and lowered.

Maintenance, risks and historical issues that are related to climate

Form

The dam structure is generally very resilient to most weather related impacts. Although the operation of water levels has changed significantly over the past few decades, leading to larger and more rapid fluctuations in reservoir water levels, this has not caused significant structural or erosional issues for the dam. Key reasons for this include:

There is a good topsoil cover and the crest of the dam is well protected by hardcore. Therefore, although the clay core is not specifically protected by a cap or membrane, the embankment maintains a good grass cover throughout prolonged dry periods, and historically there has been no history of exposed soil cover leading to erosion or desiccation.

Note: the Supervising Engineer's experience of other dams in the south of England indicates that the quality and depth of the topsoil and surface protection is a key factor in the resilience of the dam to erosion issues during or following drought periods, and will generally act as a good indicator of the risk of climate change for most earthfill dams in this area.

The upstream face is well protected by concrete slabs which protect against erosion down to the top of the berm and allow movement in the concrete during periods of high temperature and exposure to sunshine.

The impounded catchment is small and does not experience flooding or erosion during high rainfall events. The dam does not therefore tend to suffer from issues associated with catchment debris.

The lower parts of the spillway chute is naturally shaded by the dam, which reduces thermal stresses on the concrete.

Drainage and settlement records are good and historically there have been no problems.

All steelwork and the majority of the auxiliary features are contained either underground or within the main draw off tower structure.

Note: issues associated with the presence of trees on the dam face are not an issue for this reservoir, but experience elsewhere in the south indicates that many dams of this type are vulnerable because of trees on the embankment. The key concern is over combinations of factors – e.g. disease or drought stress meaning that large numbers of trees become vulnerable to uprooting during high winds and storms.

Climate related incidents and known maintenance issues

During the 1987 hurricane, damage occurred to the concrete slabs near the top of the revetment. It is thought that this was caused by extreme wave action, which resulted in large volumes of water entering the gravel slot between the top of the revetment and the base of the wave wall. This water flowed into the sand/gravel layer beneath the slabs and the rate of inflow exceeded the rate of outflow for the exposed slab section, which caused uplift to the slabs, which contributed to damage by the wave action. This issue was addressed by infilling the gap with mass concrete and a bitumen joint sealant.

Increases in demand and refill capacity over the years have caused more frequent and rapid exposure of lower parts of the dam structure. This has not been a problem on the dam face, but some evidence of wind or wave erosion was detected at the eastern abutment next to the revetment, where the concrete slabs have not been installed and the fetch of the wind had resulted in large erosion action on the lower parts of the bank slope. Rock armouring was progressively installed in this area as a result, and exposure during recent droughts indicates that this progressive approach to adaptation has worked, with no detectable slippage or erosion in that area.

For reasons of environmental stewardship (orchids are present), the face of the dam is mowed relatively late in the year. Warm, wet conditions could cause rotting mats to form following this late mowing, which could kill the grass beneath.

Function

Function is more susceptible to climatic impacts, with notable vulnerability to drought periods. Key climate related issues include:

Water supply. Various adaptations have been required to increase pumped licence capacity as demand levels have increased. Various sources are now used for pumped refill, and during times of drought stress the operators tend to have to rely on more turbid, poorer water quality sources. The size of the reservoir means that increased silt loads have not presented an issue in terms of treatment (in the short term – see below), but does affect other functions, as described below. It was also noted that the dam is 'listed' as it now contains a species of fish parasite. This hasn't yet prevented raw water transfers to the other reservoir, and screen protection is in place. However, such events could, in future, affect the function of the dam if transfers become unacceptable for ecological reasons (particularly if the Environment Agency wish to protect downstream catchments at the other dams).

> *Note: the Supervising Engineer's experience of other dams in the south of England indicates that size and depth will often act as a good indicator of the risk that changes in source water quality might have on water treatment. Small 'bankside' storage facilities can be particularly vulnerable to silt build-up, which can quickly reduce the effective storage within the reservoir if source turbidity increases, as much of the lower volumes of stored water will become unsuitable to filter/clarifier arrangements.*

Fishing. Marginal vegetation and insect habitat are very sparse due to the rapidly fluctuating level of the water, which reduces fish numbers. This fluctuation also results in the exposure of large sections of muddy margins, which reduces the amenity value of bankside fishing. Source water quality during drought periods is also an issue to the fishery, as the increased turbidity can affect fish behaviour and even numbers.

Boating. There have been problems with launching boats during drought periods, although it was noted that the problem was most significant when the operational regime was first changed and boat club members had to adapt to the larger fluctuations in water level. Some additional gravel cover has been installed to help with launching during periods of low water, but this is difficult to solve outright as the low slope of the banks means distances to the water during drought periods can be long with a consequent effect on use.

Other recreation. Blue green algae has been an issue for this reservoir, but it was noted that the causes of blooms are complex and are not simply related to weather or sunshine. The source of raw water (and hence nutrient or turbidity levels) is likely to be as important as sunshine and temperature. It is also unclear which species are present – there is some indication that climatic patterns (e.g. hot late spring or early summer events) could be particularly significant for the blooms.

The issues associated with fishing and sailing have been made more complex by the institutional arrangements at the reservoir. Because these activities are managed entirely separately from the water supply function, there is no requirement for the Water Undertaker to provide solutions to the problems that can occur. Unlike the function related issues, any impacts may not be addressed until a 'point of crisis' is reached (e.g. if the private leasee can no longer maintain a viable business). This makes gradual adaptation more difficult, as discussed below.

Climate change risk assessment and adaptation measures

The review of the main risks, impacts and potential adaptation measures produced the following notable issues and findings:

Form

The key resilience factors described previously and the good communications and integration in the inspection regime means that most climate change related factors are not a concern, and those that might apply can be dealt with through ongoing supervision and changes to the maintenance regime. Key issues and possible adaptation measures include:

- Currently there is no periodic review of long term peizometric trends. Although changes in the 6 monthly readings are reviewed, predictable historical behaviour means that longer term trends are not now analysed. Because climate change could cause a long term change in the way that reservoir levels are operated, the situation over long term piezometric trends may need periodical review with some form of trend analysis at suitable intervals.
- It is likely that the grass maintenance regime will have to change as growing seasons increase and temperatures change. There are potential issues if grass becomes too long – the grass underneath can be smothered by the cut grass, or grass may start to form tufts. This may allow desiccation of the topsoil, which could penetrate to the underlying fill material and eventually the clay core over successive cycles if maintenance regimes are not adapted. Monitoring and maintenance of grass cover is a critical adaptation measure for dams of this type where maintenance of topsoil moisture is the key to preventing desiccation.
- Factors such as existing shading, underground location and joint expansion potential are key to determining whether there might be a risk of thermal cracking or damage to concrete and auxiliary structures. Clearly these are not an issue for this dam.
- Wind and waves are a potential problem at some sites. Wen completing the guidance it is important to highlight the fact that, although climate change will not affect wind speeds, practitioners will need to consider how risks might be affected when storms and high winds do occur. For example, if increased drawdown results from changes in operating regime and water levels in response to drought and demand, then this can lead to increased exposure of vulnerable areas around the face or abutments which can be affected by wind erosion. This issue has been addressed at this site but may be a common risk for other sites as they start to experience operational changes in levels due to climate change. Similarly, drought stress or new pests could weaken trees that are growing on downstream embankments and hence considerably increase the risk and damage that is caused when a high wind event does occur.

Function

Key issues and possible climate change adaptation measures that could affect function include:

- Because of the stress that climate change will place on both the demand for water and availability of refill within the source rivers, it is likely that reservoir levels will become increasingly variable, banks and margins will be exposed for longer and refill will become more dependent on the poorer quality water sources. This is well understood for the primary purpose (water supply) and models and established planning methods are in place to allow for this. However, such changes will also affect fishing and sailing. Monitoring and adaptation of these activities to changes in operation is made more difficult by the lack of formal liaison between the Undertaker and the private commercial enterprise that runs the fishing and sailing clubs. This means that adaptation may not happen until 'tipping points' are reached e.g. if the recreational facilities were no longer commercially viable. Adaptation measures are possible, but could be expensive (e.g. putting berms in place to protect marginal vegetation and fish breeding in certain sections of the reservoir, installing special boat launching strips that extend down to the 'dead water' level). Planning and evaluation of commercial viability and cost benefit is therefore sensible, but will be difficult under the current arrangements.
- The number of water sources and the multiple destinations for water from the reservoir, means that the site is potentially very vulnerable to invasive species and parasites, which may become an issue as climate change occurs. Part of the function of the reservoir is to supply other reservoirs, and this could be curtailed if transfers started to pose an unacceptable ecological risk.

D.2 Case Study 2

Background

This study included two dams that are located in a private estate in the Midlands. They are used as fisheries and form part of a larger complex of lakes within the estate. Both are relatively small, low risk (class D and C respectively) reservoirs.

Dam form and function

Form

Dam 1 is the smaller of the two. It has been formed from the silt and clay overburden at a former quarry site. The crest varies in width but is reasonably broad (4m) in comparison to the embankment height (≈3m) and is topped by a cinder and hardcore surfaced track. The downstream shoulder is quite steep (1:2) and generally covered by trees and shrubs. The upstream face is very shallow, with stones and rubble forming a 'natural' armouring. The overflow is formed by a concrete channel with a sill, which acts as the main control on water levels in the pond (freeboard during normal water levels is around 750mm). There is a 12" valve and pipeline that can act as a secondary discharge route and which can be used to drain the lake. Most of the downstream face is covered by scrub, willow and alder, which has been occasionally removed or coppiced in the past.

Dam 2 was built in the 18th century and comprises an earthfill embankment with a vertical masonry (large sandstone blocks) wall on the upstream face. A cinder and hardcore track runs across the crest. There is significant tree and vegetation growth on the downstream face. The overflow comprises a circular drop shaft discharging into a short, straight masonry culvert and channel. This culvert is lined with sandstone blocks on the side (possibly dating back to the original construction) and a brick course on the base. There is a secondary spillway comprising a concrete paved lowered section of the embankment at the north abutment; this discharges to a shallow grass lined channel.

Function

Both reservoirs are impounding but with fairly small catchments. Dam 1 has a smaller catchment and experiences more intermittent, often turbid, inflows, so it is used for carp fishing (as the water quality is poorer). Dam 2 experiences more reliable inflows, with a significant base flow component and less silt in peak flows. It is therefore used as a trout fishery.

Management and inspection regime

The fishery staff work on the site daily, so management of tracks, vegetation and debris is an ongoing, regular process. Water quality and temperature data are gathered but only as an operational tool for the fisheries and records are not kept. Some decisions about vegetation management are made in relation to the dams, but vegetation management is usually carried out for fisheries operational purposes. Maintenance recommendations relating to dam safety are all made by the Supervising Engineer.

The Supervising Engineer visits once a year and provides an annual statement to the estate supervisor. Section 10 visits by the Inspecting Engineer visits have been on a 10 yearly basis. Maintenance suggestions, modifications and safety related capital works are provided in the usual format, with Recommendations in the Interest of Safety separated from other matters and maintenance suggestions.

Maintenance, risks and historical issues that are related to climate

Form

Maintenance activities and work on recommended actions are generally carried out by fisheries staff. Larger capital works will be contracted out by the estate management as the budget allows.

The dam forms are generally very resilient to climate related impacts. Both are in sheltered locations, are well shaded by trees and the nature of the construction (homogeneous fill with a hardcore track topping) means that they are not prone to problems such as desiccation. The masonry that is present on the face of dam 2 is formed by large sandstone blocks that do not rely on mortar to ensure their integrity. Both experience very little fluctuations in water levels. Spillways are straight and well shaded. The spillway arrangement for dam 2 is prone to blockage from reeds and other debris but is currently regularly inspected and maintained. The climate related incidents and known maintenance issues that have been recorded the two dams include:

The crest of dam 2 had been considered to be too low in comparison to the secondary spillway, meaning there were concerns of overtopping during high winds or design storm events (1 in 150 years). Recommendations were made to reduce the level of the primary spillway, but for management/operational reasons it was decided to raise the crest by around 250mm instead.

Some leakage beneath dam 1 did occur, but this was caused by the breakage of a land drain during dredging activities and was not climate or water level related.

Trees on the downstream face of dam 2 are cut back to reduce height and hence vulnerability to uprooting.

Function

Function is entirely monitored and maintained by the fisheries staff working for the estate owners. Function is more prone to climate related impacts than form, and the following ongoing issues were identified:

Water quality is a key factor that dictates how the fisheries can be run. The reservoir for dam 1 was changed to a coarse fishery, due largely to the amount of and silt that can run off from the catchment during storm events, which make the water quality unsuitable for trout fishing.

The dam system has historically proven relatively resilient to drought periods, and there is some facility for pumping between pools when inflows are low. The pools themselves only tend to drawdown very slowly, almost entirely as a response to evaporation, and fill reasonably quickly following rains. However, drought patterns are important, and the reliance on surface runoff means that extended periods of absolutely dry weather can risk water levels. Importantly, inflows of water act to cool temperatures within the pools, which are a critical aspect of water quality for the trout fishery. Fish distress is therefore likely to increase during extended drought periods.

As well as water quality, the trout fishery is prone to *Argulus* (fish lice). This is associated with warm weather, and the manager has noticed that this is becoming more problematic and is affecting the fish for a longer period each year. Currently the trout fishery has to close for two months in the summer due to the effect that this and water quality, have on the trout.

It should be noted that for fisheries, populations of midges and mosquitoes are a benefit and do not present a threat to function under current climate conditions.

Climate change risk assessment and adaptation measures

The review of the main risks, impacts and potential adaptation measures that might be associated with climate change produced the following notable issues and findings:

Form

As discussed previously, the dams themselves are inherently very resilient, and climate change is unlikely to result in direct impacts on the structures. Desiccation is unlikely to be a problem, large fluctuations in water levels are unlikely and faces are too short for direct rainfall to present an erosional risk. Design overflow facilities have spare capacity of 23% and 48% respectively, so there is a minor risk that higher 2080s scenarios could result in overtopping at the smaller dam. However, the risk is marginal and remedial works would be straightforward (as crest raising is not likely to be problematic) so a 'wait and see' approach is entirely appropriate at this site.

The risk of debris blockage at the spillway for dam 2 may increase with climate change. The current management regime effectively mitigates this risk, but this could become an issue if the fishery ceases to operate at any point in the future. In that case the visits to the spillway intake may be limited to the annual inspection, which would not be enough to address the risk, particularly as climate change may increase debris loads. This is an important point from the case study; risks from climate change depend heavily on the maintenance regime that exists at the dam, some of which is relatively informal and depends on the current use of the facility. This needs to be borne in mind by Supervising Engineers when changes of use occur at a given facility.

Tree growth is not currently a problem as it is well managed and trees are generally healthy. However, there are large numbers of trees present on the downstream face of both dams and there is a risk of damage during storms if the maintenance regime changes and heat stress or introduced diseases affect the tree population. This type of issue may need to be considered on a periodic basis by the Supervising and Inspecting Engineers.

Function

The key risk to function relates to the larger dam and its role as a trout fishery. It is vulnerable to poor water quality and high temperatures, both of which may be affected by climate change. It also appears that problems associated with *Argulus* (fish lice) may be exacerbated as summer seasons grow longer. In terms of adaptation, the main approach would be to change function in response to climatic impacts, but this has implications for commercial viability. Operators may therefore benefit from 'early warning' monitoring activities (e.g. keeping records of routine water quality and temperature readings so that they can evaluate trends on a periodic basis), as these could give advanced warning commercially damaging risks, such as fish kills. Commercial information (such as catch data) is already used to evaluate the impacts of chronic issues such as water quality and *Argulus*, but again some form of trend analysis may be useful if anecdotal evidence suggests impacts are changing in response to the climate.

Fisheries do rely heavily on abundant insect life to maintain fish populations, so climate change related disease risks such as malaria would have a profound effect on function for this type of facility. Policy (governmental) level adaptation measures that ensure operators are kept well informed of any emerging health risks are vital for this type of facility.

Because this site does not involve pumped storage, is well isolated from the downstream river and access is controlled to paying customers, it is not particularly vulnerable to invasive species or parasites, which may be an issue for other fisheries. These mitigation factors are clearly important and should be reflected in the guidance

D.3 Case Study 3

Background

This is a ‘typical’ small to medium sized Pennine type dam in an upland catchment in northern England. It forms part of a chain providing water supplies for a Water Undertaker. The dam is classified as type ‘A’.

Dam form and function

Form

The reservoir is an earthfill dam with a puddle clay core. The upstream face has a 3:1 slope with stone pitching down to an informal ‘beach’. The downstream slope is steep with a 2:1 slope, and the toe of the slope is situated in the downstream reservoir (when levels are reasonably high in that reservoir). It has ‘standard’ (250mm) topsoil cover and grass cover. Both mitres on the downstream face contain gravel drains to manage surface runoff. The catchment arrangement is complex, with by-wash channels that intercept most of the inflows and gated weir arrangements that allow water to enter the reservoir from the channels. The spillway is a masonry type.

Function

Water quality is important due the reservoir’s water supply function. The reservoir does not have any other major functions.

Management and inspection regime

Maintenance and monitoring includes routine inspection and maintenance from the Undertaker, formal 6 monthly Supervising Engineer visits and 10 yearly Inspecting Engineer visits.

It was noted that the remote location and the nature of the water industry AMP cycle means that ongoing maintenance has been limited at the site. There is a tendency for issues to be addressed through reactive capital maintenance following Supervising Engineer’s advice or Inspecting Engineer’s recommendations. To date the site has not been included within a formal Portfolio Risk Assessment, although it is understood this was ongoing at the time of assessment.

Maintenance, risks and historical issues that are related to climate

Form

There have been a number of historic issues related to climate and rainfall. These include:

- Historic landslips within the catchment. These appear to have been arrested but are related to the thin, often sandy, soils and steep gradients within the catchment.
- An additional concrete spillway was added in 1980 when the dam was upgraded to ensure it could pass the PMF.
- The crest drainage relies on a flap valve return to the upstream side of the dam. There have been some problems with this, leading to soggy conditions and resultant damage to the crest from vehicle passage.
- There is an ongoing problem where the formal stone pitching on the upstream face ties into the beaching at the base. The original design did not anticipate that this would be exposed near the water line for significant periods of time, but changes in demand mean that water levels have generally lowered within the reservoir. These lower levels mean that erosion of the beaching caused by wave action has reduced support to the base of the formal pitching and caused some blocks to become dislodged.

It was noted that the pitching itself is not directly vulnerable to climate change, but that some types of jointing might be. Polysulphide jointing materials can suffer shrinkage which can allow wave damage, and this could be exacerbated by exposure following low rainfall or high demand and hot or fluctuating temperatures during heatwaves. Open stone asphalt has proved to be a useful material to address slope pitch issues, however very hot temperatures over prolonged periods could cause this to run or flex, resulting in variable cover and weak spots on the wave protection.

- The nature of the catchment means that silt can build up within the bypass near the inlet structures. Vegetation growth is common and can become dislodged, blocking weirs and valves during subsequent high flows. Low water levels around the inlets to the reservoir means that erosion and loss of support can also be an issue where they discharge into the reservoir.
- Flow within the by-wash channels are managed via penstock arrangements. The nature of the catchment means that these are prone to silting, which can directly block the penstocks or lead to vegetation growth and associated blockage problems.
- Siltation near the original spillway crest can also be problematic with catchment runoff causing sandy ‘beaches’ to accumulate on the shallow approaches to the spillway. Vegetation growth (including small shrubs) can then occur when water levels are low.
- There has been some erosion of the bank immediately downstream of the point where the masonry walls end on the original spillway.
- The catchment is poorly vegetated so debris is not a problem for the site, except in the localised cases described above where vegetation has started to grow around the spillway.

Although there are a number of catchment erosion related problems, these do not occur on the downstream face itself, which is stable and well grassed despite the steep slope. This is because the topsoil is thick and well drained, with a properly managed sward and mitre drains are well designed and maintained. There are no clay rich areas that can cause waterlogging or wetting and drying cycles that lead to grass kill.

Function

The key current issue around function relates to water quality. High, erosional flows within the catchment increase turbidity within the reservoir, which reduces operational flexibility as it removes options or source water for the downstream treatment works.

Climate change risk assessment and adaptation measures

The review of the main risks, impacts and potential adaptation measures produced the following notable issues and findings:

Form

Low rainfall and high temperature during summer are likely to cause persistent and fluctuating low water levels as the water balance for the reservoir changes (inflows reduce and demand increases), which could exacerbate the deterioration of the base of the formal pitching. This may require increased surveillance and reactive maintenance in the short term, followed by possible remedial capital works or a change in function if the rate of deterioration increases to an extent where there are safety concerns or maintenance becomes excessive.

The poor, sandy nature of soils and steep slopes in the catchment mean that erosional degradation is likely to increase, both due to more intense winter rainfall and summer heat stress damaging the upland catchment vegetation (which is poorly conditioned for hot weather). This will tend to exacerbate the existing siltation issues around the reservoir. Again, this is likely to increase reactive maintenance requirements and adaptation measures such as routine dredging, or catchment management initiatives may be required. Silt deposition and associated vegetation growth within the spillway is also likely to worsen, requiring additional surveillance and possible eventual re-modelling of the spillway approach.

Increased frequency of operation of the spillway due to high winter rainfall is likely to worsen the downstream erosional problems. Capital works to allow increased reliance on the secondary spillway or extension of the scour protection downstream of the stilling basin may be required if ongoing surveillance and maintenance becomes too expensive or is not sufficient to address potential safety concerns.

Additional winter rainfall on the crest road is likely to worsen the existing drainage problems. Again, although this could be addressed through ongoing maintenance, it is important for the asset owner to consider the source of the problem (in this case the flap valve drainage arrangement) and consider the implications that this might have as the climate changes. Currently this can be addressed through the existing maintenance regime, however it is noted that the crest cannot drain whilst the reservoir is in flood (as water levels will cover the flap valve on the upstream side). If more intense rainfall means that the crest road is often in poor condition, then the owner should consider the risk that the crest may be effectively impassable during flood conditions if the underlying issue is not addressed.

Function

Key issues and possible climate change adaptation measures that could affect function include:

Catchment degradation (as above) leading to high turbidity and possible colouring of the water. Monitoring of catchment quality, including any desiccation or large scale drying out of peat areas and increased erosion or landslips, is likely to be important. This information should fed into Water Safety Plans and Water Resource Management Plans as appropriate.

D.4 Case Study 4

Background

This case study covered a large water supply dam in the south west of England. It is a category A dam, which is managed and owned by the Water Undertaker.

Dam form and function

Form

The reservoir has two dams. The main structure is formed of cyclopean masonry with a full width spillway which acts as a weir. It is tied into solid rock at the base and shoulders. The dam contains scour arrangements the outfalls to the masonry and rock stilling basin. There is also a shallow earthfill embankment that acts purely as a retaining structure on a low point in the reservoir perimeter. This has formal concrete slabbing on the upstream face which carries through to the toe of the embankment. There are mitre drains on the downstream face.

Function

The reservoir is used primarily for water supply with some secondary recreational use.

Management and inspection regime

The management regime is a 'conventional' Water Undertaker arrangement, with the owner basing maintenance and capital works on Supervising Engineers Statements and Inspecting Engineer's reports. Ongoing maintenance of the grass sward on the earthfill embankment and regular valve maintenance are carried out by the Undertaker.

Maintenance, risks and historical issues that are related to climate

Form

The structures are inherently extremely resilient to climatic impacts, and no significant climate related issues were identified during this case study. Reasons for this include:

The main dam is non-erodible and has no major cracks or stability issues. The spillway is large in comparison to the PMF and the stilling basin is robust. The nature of the dam spillway means that it is inherently resilient to blockage by silt or debris.

The earthfill dam is very low and has a good topsoil/grass cover. Drainage is simple and easily maintainable, with good access and no existing erosion or drainage problems.

> It was noted that some masonry dams (including cyclopean masonry) do have existing large cracks which can respond to fluctuations in temperature. These may require enhanced monitoring under climate change (particularly if structures are south facing) as changes in inflow and demand patterns may mean that large temperature fluctuations occur on the dam face whilst water levels within the reservoir (and hence thermal lag) are low.

Function

As with form, there are currently few issues with function, although this case study review did not include representatives from the operational side.

Climate change risk assessment and adaptation measures

This case study provides an example of a reservoir that is inherently resilient to climate change and is unlikely to require adaptation within the 2080 time frame. Reasons for this are presented in the text above.

D.5 Case Study 5

Background

This study involved a large network of flood storage embankments in the south of England, which have been built up through informal dredging and bunding activities over the course of several centuries. The study area encompasses over 30km of 'boundary' embankments with numerous siphon, sluice gates and structures that effectively form intermediate storage cells during flood conditions.

Dam form and function

Form

The form of the embankments is variable but they are generally around 3.4m high and are formed of homogeneous clay and silt (often the cut material arising from the construction of adjacent drainage ditches). Some of the embankments include masonry walls within the design. Many are very overgrown and some are tied into property boundaries. Siphons and sluices are of varying construction with various types of penstocks, screens and valves.

Function

Function is complex. The primary 'function' is flood alleviation, and the main embankment assets are managed under the Reservoirs Act 1975 by the Environment Agency. However the whole area is formed of arable land, there is an Internal Drainage Board (IDB) responsible for management of water levels, and there are various ecological interests, including areas of SSSI associated with the intermediate ditches.

Management and inspection regime

This particular area floods regularly, and the IDB and water management stakeholders are actively involved in the ongoing maintenance and inspection of the embankments and auxiliary structures. The Supervising Engineer Statements and Inspecting Engineer reports are organised by the Environment Agency (as the statutory owner), who is also responsible for safety critical maintenance. However, the sheer length and accessibility of the embankments (they are very overgrown in places and tenancy arrangements can make access difficult at times) means that it is difficult for the statutory maintenance and inspection process to address all of the operational and maintenance issues that might arise. Vigilance and local presence from the other stakeholders is therefore an important part of the maintenance and inspection regime.

Maintenance, risks and historical issues that are related to climate

Form

There are numerous issues over form that are directly or indirectly related to the climate. These include:

- Vegetation growth is problematic, and it is not realistic to try and keep all of the embankments clear of trees and bushes. Damage when trees fall due to disease or storms can occur.
- Burrowing animals are a particular problem. This is not directly related to climate but presents perhaps the greatest risk to the integrity of the embankments when they become filled with flood waters following high rainfall events.
- Infrequent vegetation maintenance and livestock encroachment means that damage to the crests, particularly around structures (which are often fenced and hence concentrate livestock activity), is common. Grass cover can become very poor and desiccation of fill

material around the structures can occur. This can lead to leakage or movement around the structures when flood events occur.

- Screens, valves and penstocks are regularly blocked by vegetation debris.
- Where embankments have not been formally compacted, then seepage and piping can become an issue where the earthfill has a higher silt content, particularly if the flood storage is filled for prolonged periods of time.

The key point here is that the form is highly variable and often not 'engineered' in the conventional sense. Under the current arrangements this presents maintenance challenges, but it is an old system with known issues and failings that are effectively managed as part of an ancient landscape. The biggest risk is likely to be associated with changes in the land use and hence stakeholder regime, as it would be difficult to prevent deterioration in underlying problems if maintenance and inspection became reliant on the statutory process alone.

Function

Problems with function are complex and are integrated with issues such as land management and environmental stewardship and more formal processes such as the local Water Level Management Plan. These have a significant impact on how land within the flood storage area is used and affect issues associated with form (particularly livestock damage, vegetation issues and the management of burrowing animals).

Climate change risk assessment and adaptation measures

The review of the main risks, impacts and potential adaptation measures produced the following notable issues and findings:

Form

The key point in relation to form is that the system is effectively managed based on an existing regime that includes current patterns and frequencies of flood storage and land and water management practices that have grown up around current climatic conditions. The stakeholders manage the land in response to a fairly well known pattern of inundation and land availability, and this local knowledge is vital to maintaining the flood management infrastructure. The biggest risk is therefore that climate change will disrupt patterns of inundation and land use and hence disrupt the non-statutory stakeholders and management processes that are in place. Points to consider include:

- If flooding becomes more frequent, then will the structures be able to cope in their current form? The main risk relates to piping and leakage around structures, and there may be a risk that reactive maintenance will become too onerous or even impossible during winters where the flood retention areas are filled for numerous, prolonged periods. This situation could be made worse if dry summers and wet winters lead to cyclical seasonal desiccation followed by prolonged wetting under flood conditions. Is there a risk that current land uses will no longer be tenable under climate change?
- If so, what will happen to the non-statutory stakeholders and what implications does that have for the statutory management regime? Will it become impossible to control vegetation encroachment and associated burrowing animal activity?

The adaptation process for this will have to rely on stakeholder liaison and monitoring of trends and activities. Consideration of the roles and changes in stakeholder management activities may need to be included within the statutory inspection process, and specific 'early warning' signs (such as landholder changes, marked deterioration in embankment areas etc.) may need to be included within the climate change review process. Early warning is vital as adaptation measures beyond simple monitoring are likely to be complex and will have to form part of a strategic study of the area (which will have to consider options such as abandonment, wholesale re-engineering or changes in the institutional management of the structures). This will take considerable time to review and implement, so lead times in the order of 10 – 20 years are not unlikely.

Function

The issues around function for this case study are linked to those described for form above.

D.6 Case Study 6

Background

This case study involved two medium sized earthfill clay core dams with a very similar form and function to the dam described in Case Study 4. They are located in the north of England. The main purpose of this review was to examine potential spillway issues at a dam where modification has been required following the review carried out after the Ulley incident in 2007. Both are Category A dams.

Dam form and function

Form

Clay core earthfill with a masonry spillway. Other features are similar to Case Study 4.

Function

Seasonal storage for water supply only.

Management and inspection regime

The dam is entirely managed by the Water Undertaker. They arrange regular maintenance, capital works through the Supervising Engineer Statements and Inspecting Engineer visits and reports.

Maintenance, risks and historical issues that are related to climate

Form

These dams have some of the maintenance issues associated with catchment degradation as discussed for Case Study 4. Silt and vegetation encroachment into bypass structures is particularly problematic, and there have been landslips into the reservoir as a result of poor quality, shallow, peaty soils overlying steep Millstone Grit formations. There have also been some problems with masonry jointing on the pitching, although in this case it has been due to vegetation growth and slow trickle flow across the exposed face which has degraded the joint fill when reservoir levels have been low for prolonged periods of time.

Both spillways have previously been subject to some damage and undermining during flood flows . Physical models have been constructed to evaluate hydraulic impacts from flood flows up to the PMF, and significant remedial works are likely to be required as a result of the study which indicates that replacement of the spillway channel will be required. Key points to note in relation to the spillways include:

Climate change has not been considered in the PMF calculations. The key uncertainty relates to the discrepancies that emerge due to the differences between FSR and FEH calculations. These discrepancies are reducing as CEH has reviewed the FEH PMF calculations, but this highlights the uncertainties that are already inherent in PMF assessments. It also highlights the fact that, although the new Flood and Water Management Act 2010 concentrates on risk assessment approaches, absolute deterministic methods will still have to be relied upon when engineering calculations are being made for dams and dam structures, particularly in relation to hydrology.

Access to the outer wall of the spillway can be very difficult due to rhododendron growth, which means ongoing maintenance visits to that area can be limited. The remoteness of the site also means that maintenance surveillance is generally less than at some sites. All of this needs to be taken into account when new and remedial works are being considered for the site.

Function

The only impacts are on water quality, as discussed for Case Study 4.

Climate change risk assessment and adaptation measures

The review of the main risks, impacts and potential adaptation measures produced the following notable issues and findings:

Form

For Category A dams, PMF calculations do not currently allow for climate change and there are significant uncertainties for the calculations that make such allowances difficult (PMF calculations still use the FSR methodology and models). This needs to be accounted for when climate change guidance is being produced for spillway assessment.

Exposure of pitching can promote degradation of mortar through trickle flow and vegetation growth. This is unlikely to be safety critical and can be addressed through reactive maintenance but is likely to be exacerbated through climate change and inspection and maintenance adaptation may be required.

Where catchments show evidence of historic landslips, particularly in upland peat environments, then there is a significant risk that climate change could cause further slips, even if historic movement has ceased. Monitoring of at risk areas near spillways or downstream face mitres is particularly important as these could fail during very high rainfall events and lead to 'in-combination' difficulties with spillway performance or face drainage. Where problems with catchments or structures are possible, then issues of vegetation preventing access or inspection need to be considered and adapted to.

Function

Key issues and possible climate change adaptation measures that could affect function include:

Water quality problems leading to reductions in operational flexibility, as described for Case Study 3. It was noted that landslips during the Cockermouth floods caused significant water quality problems in nearby impounding reservoirs, both from turbidity and from colour following the exposure of the underlying peat.

D.7 Case Study 7

Background

This case study centred on a Category A, concrete buttress type dam in Wales. Because the dam is inherently resilient to climate change (for reasons discussed below) discussions were widened out to examine maintenance, capital works and supervision issues faced by Water Undertakers that have not been covered in previous case studies. Notes on such issues are provided in boxed text as appropriate.

Dam form and function

Form

Large, impounding, concrete buttress dam tied into rock foundations.

Function

Seasonal storage for water supply (including some flood retention), hydropower, recreation and downstream trout and freshwater mussel fishery. A minimum low flow release has to be maintained through the dam. There is an operational management curve that incorporates up to 95% refill for water supply operations and 5% capacity is maintained for flood operation. Hydropower is only used by the Water Undertaker for electricity supply to its own operations.

Management and inspection regime

The regime at the dam is unusual, as the Environment Agency own the asset, but all operational, maintenance and supervision activities are organised by the Water Undertaker and recharged to the Environment Agency. This arrangement can complicate the maintenance regime, and minor works that are not required for safety (e.g. Supervising Engineer suggested actions) can tend to be deferred until the maintenance issue becomes safety critical or there is a strong investment driver for remedial capital works.

> Note: although this dam is inherently resilient to climate change and maintenance is not a particular concern, unusual management regimes can be a potential barrier to climate change adaptation at other sites. Where funds have to be recharged or negotiated with management organisations, or where multiple stakeholders are involved, then there can be a tendency to delay changes in maintenance or minor maintenance matters until issues require capital works. This situation can be exacerbated by financial or regulatory incentives that promote capital expenditure over operational expenditure.
>
> It was noted that it is very difficult to 'model' maintenance requirements for dams, as standard approaches such as 'mean time to failure' analysis do not apply to structures that are not allowed to 'fail' due to safety implications. In many cases the preventative maintenance suggestions made by Supervising Engineers are difficult to quantify in the same way that the impact of maintenance interventions can be quantified for other types of assets

Maintenance, risks and historical issues that are related to climate

Form

None. The dam is non-erodible and is in good condition, has a more than adequate crest spillway that is in good condition and there are no exposed auxiliary structures that are sensitive to climatic conditions. The fish farm used to be located in the upstream reservoir but was moved downstream due to concerns that it could become detached in a storm and partially block the spillway.

It was noted that there are two large cracks inside the structure, but these occurred during or shortly after construction and are not a problem to function or safety. Ongoing monitoring shows that there is no movement. All of the hydropower works are internal to the structure.

> Note: the condition of the concrete after construction will generally dictate the structural risks associated with the dam. Any vulnerability to climatic conditions (and hence climate change) will tend to be expressed through the movement of existing cracks or joints, which will tend to be well monitored within large concrete dams.

The dam face is jointed and sealed on the upstream side, and the buttresses have been sealed with water ties (bars) that contain 're-sealable' bitumen. However, these are located inside the structure, and neither joints nor ties appear to be vulnerable to climate.

Because of the nature of the crest weir, the only structural risk during high flows relates to potential over loading of the structure if very high water occurred. This has been considered and would require flows much higher than the PMF before it became a risk.

Debris can occur within the catchment, but the broad crest arrangement prevents this from being a problem. The hydropower inlet could be at risk but is well positioned for this dam. The positioning of inlets in relation to catchment debris was identified as a key consideration at other dams.

Function

Function is similar to that in Case Study 11, and was not reviewed for this case study, as representatives from Operations were not present at the meeting.

Climate change risk assessment and adaptation measures

The review of the main risks, impacts and potential adaptation measures produced the following notable issues and findings:

> ***Form***
>
> In relation to the Case Study dam, two issues relating to climate change were identified for further discussion with a concrete dam specialist:
>
> - Risks posed to existing systems of cracks caused by increased flexing during extreme temperature variations,
> - Potential for increased rate of degradation of jointing material if faces become exposed for longer periods of time.
>
> Neither of these issues were thought to represent short term safety risks or likely to result in a rapid escalation in maintenance requirements.
>
> As noted previously, other types of dams within the Water Undertaker's dam stock were considered on a general basis as part of this review. A number of key points were identified based on inspection experience and PRA type assessments of the dam stock:
>
> It was considered that high rainfall was unlikely to be a risk unless there was poor grass cover on the downstream face, in which case direct rainfall and over-topping could become an erosion risk. Maintenance of the grass sward and monitoring to identify climatic 'tipping points' that could kill the grass cover were considered to be key points for adaptation. The potential for grass fires was also raised. Because the resilience of dams in England and Wales often relies on suitable grass cover, significant changes in summer climate could put the integrity of the face at risk if grass fires become a common problem.
>
> Rapid drawdown caused by changes in refill or demand were considered to be a potential concern, especially with the 'Pennine' type homogeneous earthfill dams. These can be prone to slumping of the

upstream face, particularly if rapid drawdown occurs after the reservoir has been kept full for a prolonged period, allowing pore pressures to build up within the upstream face.

For clay cores, it was considered very unlikely that changes in climate would present a desiccation risk, unless the core is very thin, close to the face (i.e. more like a covered clay blanket) or if the grass sward is lost for extended periods of time. The exception to this was considered to be dams where burrowing animals (particularly rabbits) have infested the downstream face and a network of tunnels is in place that allows air movement through to the core. In that case, desiccation is feasible during very long, hot summer conditions.

Trees, either on the face or in catchments where tree fall could cause blockage of the spillway, could be a concern, particularly if heat, drought stress or new pests or diseases weakened large trees prior to a major autumn storm event.

Function

It was noted that up to 25% of the dam stock is no longer used for water supply, and the asset owner is seeking to implement a programme of risk reduction measures before the asset is sold on.

D.8 Case Studies 8 to 10

Background

For this set of case studies, three flood storage reservoirs of various sizes, form and function in the north of England were reviewed to examine the range of climatic issues that might affect this type of dam.

Dam form and function

Form

Dam 8: Category C, small, offline reservoir. Completely bunded (one section is formed of a railway embankment), uncompacted homogeneous embankments. Filled automatically during high river flood operation via a depression in the embankment at the upstream end. Emptied via twin penstock escape sluices at the downstream end (incorporating a concrete headwall and 1m tunnel inlets).

Dam 9: Category B, medium-large, offline reservoir with uncompacted homogeneous fill embankments. Formed of two separate sections located either side of the river, with a number of inner embankments forming cells within the eastern section. Contain a series of spillways linked to a central gate on the river. No penstocks or gates; all operation is via gravity (feed and emptying).

Dam 10: Category A, modern, 12-14m high, cross catchment impounding reservoir. Embankments are formed of compacted homogeneous fill and there is grasscrete protection on the crest. There is a large, grassed, concrete spillway (interlocking concrete sections with grass cover over the top) and twin GRP-lined culverts fitted with hydrobrakes to allow up to 14 cumecs to pass through the embankment when full. There is a series of trash poles on the upstream inlet to catch large debris during flood flows.

Function

Dam 8: Flood storage only. The area within the base is farmed.

Dam 9: Flood storage, with recreation and birds and wildlife in permanent lakes in the centre of the upper storage cells on the eastern side. The western section forms a large, permanent lake that is used as a recreational facility (walking, water sports). It is only used for flood storage as a 'last resort' within the network of flood storage measures along the river.

Dam 10: Flood storage only. Impounded area is kept free of recreation, farming etc.

Management and inspection regime

Operational Delivery has a maintenance programme that is formed of ongoing grass cutting maintenance, three monthly maintenance inspections of penstocks and one monthly maintenance inspections of larger structures. Some vermin control is also carried out in winter. The Environment Agency Asset Systems Management department relies on the six monthly (April/May and September/October) Section 12 Supervising Engineer's Statements for all other maintenance recommendations.

For Dam 9, the recreational activities are run by the Local Authority.

> Note: Many of the washlands are being turned into wetland areas for ecological benefits (this includes designated SSSIs), and Natural England, Wildlife Trusts, Royal Society for the Protection of Birds (RSPB) and others often become involved as stakeholders. This can result in difficulties over vegetation management, vermin around heavily vegetated areas and problems with accessing the dam crests (any changes are normally kept away from key structures). It also adds another dimension to the functioning of the reservoir. Access to washlands can also be problematic as many are farmed, although arrangements for access will exist in some form at all of the sites.

Maintenance, risks and historical issues that are related to climate

Form

Dam 8: The following points were noted:

- Vegetation is an issue, particularly as hawthorn and other bushes are common on the crest and can grow quite large. Grass cutting can be sporadic and inadequate.
- Some areas suffer from bare patches and erosion, often caused by cattle damage associated with muddy conditions on the crest and around the penstock.
- The land use within the washland changes regularly and there is no requirement to keep the Environment Agency informed. Livestock damage or ploughing close to the embankment is therefore intermittent and not predictable.

Dam 9: As with dam 8, the long embankments involved means that vegetation growth is an issue. Trees and shrubs have historically grown on the entry spillway, which affects both form and function.

The crest levels are not even, and there have been concerns that low spots could promote concentration of discharge overtopping during flood events.

Dam 10: This is a relatively new scheme, so there are relatively few issues with the embankment itself. The following issues were noted:

- There are some wet spots and sinkhole development on the right downstream mitre. This is being investigated.
- The inlet channel is too wide. This has resulted in the main stream course largely bypassing the trash poles and caused silt to build up between the poles.
- There is some erosion of the access track near the downstream stilling pond caused by rainfall.
- There is some abutment damage due to horses, and moles have been found in the embankment.

Note: It was noted that vermin issues tend to occur in more heavily farmed, lowland areas where there is more food and vegetation cover.

Function

The dams are rarely used for their primary function. Dam 8 was entirely overwhelmed by the 2007 floods and essentially lost its function (the dam was later re-evaluated as being effective up to a 1 in 50 year event). For Dam 9, the Local Authority seeks to avoid the Environment Agency using the recreational lake for flood storage, as this affects water quality. Currently this facility is only used very rarely (twice since the 1970s).

Climate change risk assessment and adaptation measures

Based on the study subjects, and on known issues with other flood storage dams in the area, the following issues were identified in relation to climate change:

Form - washlands and other types of older non-impounding structures

Although many of the 'non-engineered' (i.e. uncompacted) homogeneous embankments do have problems with vegetation, vermin, poor crest drainage and livestock damage, they are often very wide in relation to their height, so stability and integrity is not generally at risk. For example, Dam 8 did not suffer significant impacts during the 2007 event, even though flood waters spilled freely down the vehicle entry ramp for extended periods. Therefore, although the hotter weather and more intense rainfall patterns associated with climate change may exacerbate erosion and vegetation issues and cause flood retention structures to fill more regularly, many flood retention dams will be inherently resilient to these changes. Risks to stability and maintenance problems are only likely to occur if there are specific factors that cause vulnerability in the dam structure. These can include:

- Erosion around structures, particularly where headwalls are involved. Erosion could reduce crest height at these locations or provide preferential flow paths, leading to concentrated flows and progressive failure during high water or over-topping events. As well as increasing the likelihood and frequency of such events, climate change could also increase erosion rates, particularly if they are associated with poor drainage or wetting or desiccation cycles (possibly combined with livestock passage).
- Areas where ditches, intrusive farming activity or other issues have resulted in lower embankment stability or preferential drainage pathways beneath the dam. The risk of failure at these points will increase as the frequency of flood inundation increases with climate change.
- Areas around structures where burrowing animals have reduced stability and promoted internal desiccation and weakness. These can serve as preferential flow routes and promote piping and erosional failure when the reservoir is full. These issues tend to occur more often in areas where maintenance and inspection access has become problematic due to vegetation encroachment and/or poor drainage. Climate can affect both vegetation growth rates and the frequency and height of inundation events.
- Washland type structures with long fetches often have poor wave protection on the inside face. This can be a problem if the structures are slow to empty and inundation is frequent, as waves and wave surcharge can cause erosion or waterlogging around structures and access roads.
- Access roads tend to be low points on many structures. These are generally not a problem but could be if climate change causes excessive rutting and loss of grass cover, particularly for higher embankments that might incorporate a curved or oblique ramp.

Many of the above issues will simply require monitoring and changes in maintenance regimes (e.g. different grass management, changes in vegetation management, exclusion of livestock etc.) to prevent them becoming a risk during repeated flood events. However, the large number of structures, the access difficulties and multiple stakeholders means that there may be institutional barriers to such slow adaptation measures. This needs to be

Form - impounding flood storage reservoirs

Particular issues that need to be considered for these types of structure include:

- Standard design allowances on spillways for climate change are currently 20% of the design flood volume. This will apply to all newer structures installed by the Environment Agency.
- Some dams that have small outlet capacities can cause water to impound for prolonged periods of time into areas where trees have become established. Multiple, prolonged inundation can kill the trees, causing them to uproot and block the spillway during subsequent flood events. This type of issue is likely to get worse as flood frequency and hence the frequency of use of the impounding reservoir increases.
- Some of the 'green' spillway designs (such as those used in Dam 10) may be vulnerable to climate change as they incorporate thin topsoil cover on top of non-continuous concrete bases. These arrangements will tend to suffer from drying out and loss of grass cover during higher temperatures and prolonged drought conditions. Although such designs usually allow for some damage to the grass cover during infrequent spillway operation, the grass and topsoil still forms an integral part of the resilience of the spillway. If the grass cover disappears and the topsoil is eroded between flood events, blocks can become exposed and may be damaged by animals or vandalism. This makes the spillway blocks more prone to lifting and failure during storm flow operation.
- Some newer dams incorporate poorer topsoils with wildflower meadow mixes for environmental reasons. These will be inherently more vulnerable to heat stress, loss of cover and hence erosion when compared with 'standard' grass-cover dams.
- Increased debris and flow rates may cause problems with inlets to flow-through facilities, causing approach channels to silt up more quickly or cease to operate properly. This can be addressed through dredging and maintenance but may reach a point where this is no longer practicable.

The above issues generally relate to the design of the dam and will tend to increase maintenance costs and operational problems over time. Capital works, or even changes in use may be required if maintenance burdens or risks become unacceptable, however it is likely that there will be long lead times before such interventions are required. Works management systems or similar methods for recording historic maintenance activities may

Function

The key issue for function is to consider how return periods and sizes of flood events might be affected by climate change. It is likely that the facility will need to function more frequently as climate change occurs, and the effects that this might have on form of the dam (as discussed above) needs to be considered. The impact of climate change on the overall functioning of the flood defence system for the particular river system will also have to be considered, however procedures for developing flood defence strategies already incorporate climate change allowances.

Other potential impacts on function include:

- Frequent inundation of floodwater into reservoir areas that are currently used for recreational activities may be result in unacceptable water quality within those reservoirs. Recreational functions may therefore have to be modified in response to climate change.
- Land use patterns may have to become more regulated if vegetation or encroachment problems become a concern. This could affect the management and maintenance regime associated with the reservoir, so planning of consequences will be required (e.g. there is no point in trying the regulate farming within a washland if that causes it to become abandoned and overgrown with bushes).
- Ecological functions (such as wetlands within the reservoir area) may have to adapt if flood inundation becomes more frequent. It is easier to adapt if potential impacts and changes are considered well in advance, which will require ongoing liaison with relevant stakeholders such as Natural England, RSPB, Wildlife Trusts and local environment groups.

D.9 Case Study 11

Background

This case study centred on a series of category A, cyclopean masonry type dams forming an integrated valley system in Wales. The dams themselves are inherently very resilient to climate change because of their construction. This case study was selected primarily for the evaluation of potential impacts on function, as the system incorporates hydropower and relatively complex control curves for water supply.

Dam form and function

Form

Impounding, cyclopean masonry type dams tied directly into rock foundations. All dams incorporate full crest spillways.

Function

Seasonal storage for water supply, hydropower, recreation and farming and forestry within the catchment. The hydropower scheme is a relatively recent addition to the system (which includes some dams that are more than 100 years old), and only operates when reservoir levels are close to Top Water Level (TWL). The hydropower relies on head differential within the system; no water is actually lost from the lower dam as a result of hydropower generation. The operating rules for the system include target levels for each dam that tie into the overall percentage storage within the system. All water supply is taken from a single draw off tower in the lower reservoir. There is a slight complication to the system, as a transfer tunnel has to be used to move water from the largest dam to the lowest dam during low water levels. This is caused by the presence of an old, usually submerged dam within the reservoir footprint of the lower dam.

Management and inspection regime

As with many of dams in this area, the ownership and management of the dams is complex. The system is operated and maintained by via a service level agreement (SLA), as the system's primary purpose is to supply raw water to a SLA organisation's water supply network. The hydropower scheme is privately owned. The catchment is now managed by a charitable trust which includes a number of land owners and environmental stakeholders.

The SLA includes daily visual checks, a weekly surveillance walk through (with check list pro formas) and monthly piezometer and-notch weir readings. All capital works and non-routine maintenance are based on Supervising Engineer's advice and Inspecting Engineer's recommendations. It was noted that the ownership and management set up does make it difficult to manage the asset within the normal asset management framework, although to date the resilience of the dam assets means that this has not been problematic and all issues are adequately detected and addressed through the statutory inspection regime. However, it does mean that modifications to dam function would be more difficult to implement if they are required to optimise water supply arrangements in the future.

Maintenance, risks and historical issues that are related to climate

Form

None. The only significant historic issues have been calcite clogging of pressure relief drains (caused by leaching from the concrete) and issues associated with valve seizing. Neither of these is related to climate. Debris can occur within the catchment, but the broad crest arrangement prevents this from being a problem.

Function

There are a number of potential impacts that climatic variation can have on function. These are:

Water quality tends to vary seasonally. Unlike other sites, turbidity is very low, but the peaty nature of the catchment means that colour and metals (iron, manganese, aluminium) tend to vary seasonally, either with high rainfall, or during periods when beaching is exposed and leached by wave action. Historically this has not presented a problem, as the on-site treatment works only contain roughing filters, and the ultimate receiving works contain large scale, advanced water treatment facilities. The situation has actually improved recently, as the National Trust limits activities such as burning or unsustainable farming practices. This has increased the resilience of the catchment to climatic impacts.

The operation of the cross-connection tunnel during low water levels can be problematic, as it is a manually operated system that only has around 4ft (1.3m) of driving head. This means there is a danger of water being ‘lost’, or of yield being artificially constrained if manual operations do not accurately predict drawdown rates and demands during drought conditions. The tunnel screens are also prone to blockage (vegetation, dead sheep etc).

The overall system has a high yield in relation to its storage, which is as a result of its historically reliable, very high annual rainfall (around 70 inches, 1780mm). However, this does mean that it will tend to empty relatively quickly under prolonged autumn drought conditions, and drought intervention measures (primarily a reduction in the downstream compensation flow) have a limited impact on security of supply, as they are small in comparison to the yield and tend to act for a short period before the system runs dry. The 2003 drought led to alternative water resource schemes being implemented within the downstream supply system to offset this risk.

The hydropower plant does rely on regular high water levels to maintain production and hence financial viability. However it was noted that recent increases in the value of renewable energy has dwarfed any trends in rainfall or climate that might have occurred over the life of the asset.

Climate change risk assessment and adaptation measures

The review of the main risks, impacts and potential adaptation measures produced the following notable issues and findings:

Form

None. The assets are inherently extremely resilient to climatic variation.

Function

Water quality is potentially at risk from climate change, although this is only likely if there is widespread damage to the catchment peat bogs. Currently these are well maintained and climatic variations result in easily manageable fluctuations in water quality. Historic evidence has shown that individual drought events have not resulted in significant problems. The main climatic risk is from systematic trends in groundwater levels in the peat, caused by changes in rainfall patterns and increases in temperature. Adaptation in this case would involve an initial risk assessment to determine the vulnerability of the receiving treatment works to changes in water quality (the best approach might be to compare water quality at this site against sites with known degraded peat bog catchments). This would be followed by monitoring of temperature and rainfall trends, with the degree of assessment driven by the assessed level of risk. If there is a risk from abrupt changes in water quality, then 'tipping points' and 'early warning' thresholds can be established based on monitoring of water levels in the peat (using dip wells) and the level of encroachment of dryland species (heather etc). These would need to be supported by plans for remedial works at the downstream treatment plans, or plans for adaptation of the catchment to reduce the risk if 'early warning' thresholds are breached. Adaptation of the catchment is likely to be viable at this site given the presence of the National Trust – this should be reflected within any adaptation plans.

Reservoir yield is obviously at risk, and the Water Resources Management Plan process uses established methods for evaluating the impact of changes in rainfall or evapotranspiration on reservoir yield. However, it is noted that the high yield in relation to storage for this system means that it is potentially very vulnerable to changes in drought duration, which is not covered by the rapid assessment approaches that have been used in recent industry standard documents (e.g. UKWIR CL09). Modelling based on stochastic approaches (using weather generators) are therefore likely to be required in future in order to understand the real risk to water resources for this system. If the evaluation shows that longer droughts become more likely and more frequent, then, along with WRMP based adaptations, some modification to the tunnel between the lower reservoirs may be advisable given the increased risk of blockage and the need to ensure that yields are optimised in future.

Theoretically, the viability of the hydropower plant could be affected by climate change. However, in practice this is unlikely for three reasons:

- Although drought duration and peat groundwater levels within the catchment might be affected by climate change, predicted regional increases in winter rainfall under climate change mean that the average frequency and duration of periods of high water levels is unlikely to reduce significantly. The overall change in output is therefore likely to be low.
- In this case there is no 'trade-off' between water supply and hydropower, as there is no loss of resource from the system as a result of the hydropower supply. This means

that there is no risk that increases in demand for water supplies will reduce hydropower availability.

- As climate change progresses, then it is highly likely that the cost of carbon, and hence the value of renewable energy supplies, will continue to increase.

Finally, it is noted that, even if the scheme did become non-viable, the engineering arrangement means that the hydropower plant could be 'mothballed' without any implications to the maintenance of the other reservoir functions.

Overall the hydropower function is a good example of a theoretical impact from climate change that can actually be discarded as a real risk due to the underlying factors at the site. Some, or all, of these factors are likely to apply to most hydropower schemes in England and Wales.

Appendix E :Adaptation response to form

ATKINS

Table E.1 - Adaptation responses to form

Dam form		Climate variable	Potential impact	Future vulnerability	Adaptation responses for existing dams					Policy adaptations and adaptations for future dams		
					Long term planning	Remedial Works	Operation & maintenance	Inspection	Decommissioning	Policy & regulation	Long term planning	Design
Erodible	Clay core and homogenous Clay construction	High rainfall	More rapid fluctuations in operating water levels possibly leading to increases in pore pressure. This includes rapid fill or emptying (as an operational response) in advance of heavy rains. Risk of piping failure or mass instability as a result.	High			Use forecasting techniques to predict high rainfall events. Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall.	Reflect in inspection regimes. Increase pore pressure monitoring if at risk, increase frequency of monitoring for instability or erosion of upstream face.				Consider issue at design stage; design for rapid fluctuations and consider emergency response in advance of heavy rains.
			Water levels above design levels results in a risk of overtopping and erosion of the downstream face.	High	Review capacity and safety measures and determine long term needs.	Increase capacity through dam raising. Include downstream erosion measures - retrofit to existing dams.				Increase factor of safety requirements on peak flows and design storms.	Increase planned capacity of reservoirs.	Increase return period of design events. Include downstream erosion measures.
			Direct rainfall may cause erosion of dam face (normally downstream).	High	Consider need for covering of downstream face through long term measures e.g. establish change in vegetation.	Include downstream erosion protection measures. Retrofit to existing dams. Coverings for downstream face - e.g. plant vegetation.	Review grass cover and cutting regime to ensure grass is not lost during wet or dry periods.	Reflect in inspection regimes; increased vigilance on downstream erosion. Enhance monitoring around structures.				Include downstream erosion protection measures. Design coverings for downstream face - e.g. plant vegetation.
			Higher water levels may lead to an increase in seepage (flow paths may exit higher up on downstream face).	High			Use forecasting techniques to predict high rainfall events. Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall.	Reflect in inspection regimes; increased vigilance on evidence of seepage.				
			For reservoirs sited in floodplains, elevated flood risk may lead to greater erosion and damage to reservoir toe. Long-term repeated, seasonal exposure to flooding could reduce reservoir toe integrity.	Medium		Include erosion protection measures at the toe. Retrofit to existing dams.		Reflect in inspection regimes; monitor for erosion impacts on the reservoir toe if dam is at risk.		Enhanced inspection regime for reservoirs in floodplains.	Site reservoirs outside the floodplain where possible.	Design more robust erosion protection measures at the toe.
		Low rainfall	Desiccation and shrinkage of clay core and dam shoulders (clay core); desiccation of clay from surface for homogeneous dams. Leads to seepage and possible piping failure.	High	Plan for long term programme of retrofitting caps to clay cores to prevent them drying out (synchronise with other large capital works such as dam raising).	Retrofitting of caps for clay cores. For homogeneous dams consider protective covering on the downstream face (e.g. vegetation) or toe filters (low dams). May need to consider retro-fitting of additional drainage for larger dams.	Potential need to irrigate dam shoulders to prevent drying out in the short term.	Reflect in inspection regimes; monitor for evidence of core shrinkage - cracking at surface. Increased vigilance against burrowing animals.				Design dams with a cap to protect clay core.

Dam form		Climate variable	Potential impact	Future vulnerability	Adaptation responses for existing dams					Policy adaptations and adaptations for future dams		
					Long term planning	Remedial Works	Operation & maintenance	Inspection	Decommissioning	Policy & regulation	Long term planning	Design
			Loss of vegetation cover, increasing the risk of cracking and reducing surface erosion protection.	High	Look for more drought tolerant species, long-term programme of re-vegetation using drought tolerant species.	Use a drought tolerant species mix.	Potential need to irrigate vegetation cover to prevent drying out in the short term.	Inspect vegetation cover for signs of desiccation during summer.		Review conservation policy to allow more drought tolerant non-native species mixes.	Plan vegetation policy in advance; research new species where required.	Use drought tolerant species mix in design.
			May result in lower water levels, exposing unprotected sections of the dam face to erosion.	High		Increase capacity through dam raising. Include upstream erosion protection measures. Retrofit to existing dams.		Inspect for signs of erosion or slumping on the upstream face during periods of low water levels (if dam at risk).				Include upstream erosion protection measures in design.
			Decreases in summer rainfall can lead to more pronounced, more regular cycles of dam wetting and drying, potentially leading to slumping of the upstream dam face.	Medium				Reflect in inspection regimes; increase pore pressure monitoring if at risk, increase frequency of monitoring for instability or erosion of upstream face.				Consider in design, allow for long periods of low water levels.
		High temperature	Increased evapotranspiration contributing to desiccation and shrinking of clay	Included in desiccation from low rain	See above	See above	See above	See above				Design dams with a cap to protect clay core.
			Increased vegetation growth on dam face, if co-incident with increased rainfall. Increased maintenance requirements.	High		Use slow growing species	Increased maintenance requirements - vegetation cutting.	Regular vegetation inspection during summer.		Review conservation policy to allow more slow growing non-native species mixes.		Use slow growing species.
Erodible	HDPE liner	High rainfall	Water levels above design levels results in a risk of overtopping and erosion of the downstream face.	High	Increase capacity of reservoirs, raise dam heights.	Increase capacity through dam raising. Increase downstream erosion protection measures. Retrofit to existing dams.	Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall.	Reflect in inspection regimes; increase monitoring for erosion on downstream face following exceptional rainfall.		Increase factor of safety requirements on peak flows and design storms.	Increase planned capacity of reservoirs.	Design in downstream erosion protection measures.
		High temperature	HDPE is vulnerable to UV light; it leads to more rapid degradation of the material. High evaporation rates arising from high temperatures may lead to low water levels and increased exposure of liners to sunlight.	Medium		See below	See below	See below	See below			See below
		Low rainfall	Low water levels and hence exposure of HDPE liner to sunlight.	Medium		Cover liners (if possible).	Provide temporary cover for liners during heatwaves.	Reflect in inspection regimes; review condition of liners after heatwave events.	May lead to earlier decommissioning.		Consider introducing alternatives into the market.	Design dam to avoid exposure.
		Wind	Wind can lift liners if there is no overburden in place. Risk largely associated with exposure rather than increased wind speed. Causes slumping and mass instability.	Medium		Increase overburden or weight liners.		Reflect in inspection regimes; review condition of liners after drought events.	May lead to earlier decommissioning.			Design increase in overburden or control curves that prevent exposure.

Dam form		Climate variable	Potential impact	Future vulnerability	Adaptation responses for existing dams					Policy adaptations and adaptations for future dams		
					Long term planning	Remedial Works	Operation & maintenance	Inspection	Decommissioning	Policy & regulation	Long term planning	Design
	Concrete liner	Low rainfall	Low water levels can lead to exposure of liner, increasing susceptibility to thermal cracking.	Medium		Provide shade to reservoir edge e.g. Trees. Cap or dig out surface concrete and replace with better adapted mix.	Provide temporary cover for liners during droughts.	Inspect for signs of thermal cracking as part of monitoring regime.	May lead to earlier decommissioning.			Design concrete to cope with exposure at relevant temperatures.
		High temperature	Increase in thermal cracking and spalling of concrete liner.	Medium		Cap or dig out surface concrete and replace with better adapted mix.	Provide temporary cover for liners during droughts.	Inspect for signs of thermal cracking and spalling as part of monitoring regime.	May lead to earlier decommissioning.			Design concrete to cope with exposure at relevant temperatures.
			UV damage to concrete and joint materials.	Medium		Cap or dig out surface concrete; improve engineering of joint spaces.	Provide temporary cover for liners during droughts.	Inspect for signs of damage to concrete and joint materials.	May lead to earlier decommissioning.			Design concrete to cope with exposure at relevant temperatures.
	Asphaltic concrete	High rainfall	When co-incident with wind can result in wave action at higher levels on liner and dam.	Medium		Increase downstream erosion protection measures. Retrofit to existing dams.	Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall.	Reflect in inspection regimes; increase monitoring for erosion on downstream face following exceptional rainfall.			Increase planned capacity of reservoirs.	Design liners and dam construction to allow for higher water levels.
		Low rainfall	Low water levels can lead to exposure of liner, increasing susceptibility to block cracking.	Medium		Replace liner (better adapted mix).	Provide temporary cover for liners during droughts.	Reflect in inspection regimes; monitor for signs of failure following drought events.	May lead to earlier decommissioning.			Design to cope with exposure and relevant temperatures.
		High temperature	Increase in block cracking of liner if asphalt dries out. May resulting in slumping and mass instability.	High		Replace liner (better adapted mix). Patch mending of cracks.	Provide temporary cover for liners during droughts.	Reflect in inspection regimes; monitor for signs of failure following drought events.	May lead to earlier decommissioning.			Design to cope with exposure and relevant temperatures.
			Increased temperatures may result in reduced performance of current asphaltic binding mixes..	Medium		Replace with altered binding mix.						Design binding mix to cope with exposure and relevant temperatures.
			Diurnal temperature variations can lead to longitudinal cracking.	Medium				Inspect for signs of thermal cracking as part of monitoring regime.				
Non-erodible	Masonry, concrete	High rainfall	Water levels above design levels results in a risk of overtopping.	Medium	Review capacity and safety measures and determine long term needs.	Increase capacity through dam raising. Include downstream erosion measures - retrofit to existing dams.	Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall.	Reflect in inspection regimes; increase monitoring for erosion on downstream face following exceptional rainfall.		Increase factor of safety requirements on peak flows and design storms.	Increase planned capacity of reservoirs.	Increase return period of design events.
			Water levels above design levels result in risks of sliding and overturning.	Medium	Review capacity and safety measures and determine long term needs.		Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall.			Increase factor of safety requirements on peak flows and design storms.	Increase planned capacity of reservoirs.	Increase return period of design events.
		High temperature	Thermal expansion resulting in cracking and spalling.	Medium		Dig out or replace with better adapted materials if feasible. Re-engineer joints if required.		Inspect for signs of thermal cracking and spalling as part of monitoring regime.	May lead to earlier decommissioning.			Design to cope with exposure at relevant temperatures.
			UV damage to concrete & masonry or jointing	Medium		Dig out or replace with better		Inspect for signs of UV damage as part of	May lead to earlier decommissioning.			Design to cope with exposure at relevant temperatures.

Dam form		Climate variable	Potential impact	Future vulnerability	Adaptation responses for existing dams					Policy adaptations and adaptations for future dams		
					Long term planning	Remedial Works	Operation & maintenance	Inspection	Decommissioning	Policy & regulation	Long term planning	Design
			materials.			adapted materials if feasible.		monitoring regime.				
All	Spillways	High rainfall	High flows and water levels exceeding spillway designs can result in spillway failure.	High		Increase spillway protection and capacity.		Need to look for evidence of erosion impacts on spillways.		Increase factor of safety requirements on peak flows and design storms for spillway design.		Design larger spillways.
			High rainfall hence flows may increase transport of debris, potentially damaging or blocking spillway.	Medium	Catchment management to reduce sources of debris on spillway.		Increased maintenance requirements - removal of blockages during periods of high rainfall.	Reflect in inspection regimes; check for drought/heat stress on tree population, increase monitoring for erosion/instability following exceptional rainfall.			Catchment management to reduce sources of debris on spillway.	Allow for risk in spillway design.
		High temperature	Possible cracking of concrete spillways during heat waves.	High		Cap or dig out surface concrete and replace with better adapted mix.		Reflect in inspection regimes; increase monitoring for cracking or spalling following heatwaves	May reduce lifetime of spillway.			Design to cope with exposure at relevant temperatures.
	Auxiliary structures	High rainfall	High rainfall hence flows may increase transport of debris, potentially damaging dam components.	Medium	Catchment management to reduce sources of debris.	Cap or dig out surface concrete and replace with better adapted mix.	Increased maintenance requirements - removal of blockages during periods of high rainfall.	Reflect in inspection regimes; check for drought or heat stress on tree population, increase monitoring for erosion/instability following exceptional rainfall.			Catchment management to reduce sources of debris.	Innovative silt and sediment trap or forebay designs or inlet control designs required.
		High temperature	Possible cracking of concrete channels and wave walls.	Medium				Reflect in inspection regimes; increase monitoring for cracking or spalling following heatwaves.				
			Expansion of metal elements (e.g. steel lining of tunnels, overflow valves) in excess of design tolerances.	Medium		Possible replacement with other materials if metal elements no longer meet temperature design tolerance.		Inspect metal elements for signs of expansion (e.g. cracking of surrounding material) during and after high temperature events.				Increase design tolerance to high temperatures. Consider alternative materials if metal elements no longer meet temperature design tolerance.

Appendix F : Adaptation responses to function

Table F.1 - - Adaptation responses to function

Dam function	Climate variable	Potential impact	Potential vulnerability	Adaptation responses for existing dams					Policy adaptations and adaptations for future dams		
				Long term planning	**Remedial Works**	**Operation & maintenance**	**Inspection**	**Decommissioning**	**Policy & regulation**	**Long term planning**	**Design**
Flood detention	High rainfall	Increased flow into reservoirs increases flood risk: increased storage requirements or less well managed floods.	High		Raise dam crest or spillway to increase capacity. Increase spillway capacity.	Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall. Early-warning systems for flooding, real-time information and flood hazard mapping. Increased use of flood forecasting tools.	Monitor frequency of spillway operation, etc. Increase inspection for erosion.	If dam cannot be adapted to manage risk of increased inflows, may need to be decommissioned.	New design regulations relating to peak flows and design storms for storage purposes. More dams may be required, planning will need to facilitate this.	More flood defence dams, to protect or support existing assets or to replace decommissioned assets.	Design for more frequent and extreme rainfall events. Increase design capacity to increase flood storage capacity. Design-in resilience to overtopping - increased spillway volumes, erosion protection.
		Increase in sedimentation during flood events could lead to reduction in flood storage capacity and/or blockage of spillways due to increased mobilisation of vegetation in flood flows.	Medium	Model reduced storage volumes. Plan for significant maintenance activities such as de-silting.	Retrofitting of sediment control traps or sluice valves.	May require changes in operating approaches to promote sluicing during events and hence reduction in sedimentation.	Monitor depth when appropriate.	May result in earlier decommissioning of some dams.	Increased sediment control regulations, land use control in catchments.	Plan for significant maintenance activities such as de-silting.	May result in a need to allow for a percentage volume loss for sedimentation in design. Innovative silt and sediment trap or forebay designs or inlet control designs required.
	High temperature	Increase in vegetation growth - potential reduction in reservoir capacity and/or blocking of spillways.	Medium	Model reduced storage volumes. Plan for increased vegetation maintenance requirements.		Increased operational & maintenance requirements in terms of vegetation clearance to maintain storage volumes. Catchment management to reduce presence of invasive or fast growing species.	Monitor vegetation levels and control techniques.	May result in earlier decommissioning of some dams.	Regulations to require maintenance of flood storage volumes may be prudent. Land use control in catchments.	Model reduced storage volumes. Plan for increased vegetation maintenance requirements.	May result in a need to allow for a percentage volume loss for vegetation in design. Specification of planting and grassing details may change.
Storage for seasonal use	High rainfall	High rainfall events leading to increased peak flows into impounding reservoirs can lead to overtopping. Dams may need to be operated at lower or more variable levels to mitigate against this risk, potentially reducing available storage.	High	Modelling of available yields using different control curves.	Raise dam crest or spillway to increase capacity. Increase spillway capacity.	Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall. Increased use of flood forecasting tools.	Monitor frequency of spillway operation, etc. Increase inspection for erosion.	If dam cannot be adapted to manage risk of increased inflows, may need to be decommissioned.	Reduced available storage from existing dams will put pressure on other water resource options and may require new dams; planning system changes to enable this adaptation. Regulation to require changes in land use policy, alternative flood management options or water demand options.	Modelling of available yields using different control curves, planning for new resources and dams.	Consider uncertainties in control curves in dam design. Design-in resilience to overtopping - increased spillway volumes, erosion protection.
		Increase in sedimentation during flood events could lead to a reduction in water storage capacity.	Medium	Model reduced storage volumes. Plan for significant maintenance activities. Revise operational quality controls (e.g. blending) or consider alternative water	Retrofitting of sediment control traps or sluice valves. May result in a need to allow for a percentage volume loss for sedimentation in design. Catchment	May require changes in operating approaches to promote sluicing during events and hence reduction in sedimentation. More frequent de-silting required.	Monitor depth when appropriate.	May result in earlier decommissioning of dams if they cannot be adapted to increased sedimentation.	Increased sediment control regulations, land use control in catchments.	Model reduced storage volumes. Planning for significant maintenance activities. Planning for new resources and dams or new treatment techniques.	Innovative silt and sediment trap or forebay designs or inlet control designs required. Retrofitting of sediment control traps or sluice valves. May result in a need to allow for a percentage volume loss for sedimentation in design. Catchment management to

Dam function	Climate variable	Potential impact	Potential vulnerability	Adaptation responses for existing dams					Policy adaptations and adaptations for future dams		
				Long term planning	Remedial Works	Operation & maintenance	Inspection	Decommissioning	Policy & regulation	Long term planning	Design
		Increase in turbidity during flood events could leading to water clarity and quality issues with resultant increased treatment requirements. Water may no longer be suitable for some uses at certain times of year.	Medium	sources. May need to prioritise uses.	management to reduce sediment inflow.		Increased water quality monitoring.			Potential need to re-assess water quality standards for different uses or consider alternative water sources. May need to prioritise uses.	reduce sediment inflow.
	Low rainfall	Lower rainfall will lead to lower flows, decreasing reservoir levels and less water will be available for use. Reduced yields.	High	Review drought curves to confirm up to date and appropriate. Review drought responses and triggers. Prioritisation of water uses.	Increase storage capacity to optimise storage of winter rainfall events.	Balancing use of different water resources over seasons and across areas. Prioritise water uses.			Review drought intervention measures and implementation. Demand management policies, increased frequency of water restrictions. Reduced or variable environmental minimum flow targets (experience in Victoria, Australia). Water grid or decentralisation of water supply. Seasonal tariffs to reduce peak demands at time of greatest supply demand balance risk and environmental need. Prioritisation of uses, regulation against some uses at certain times.	Potential requirement for more water supply storage dams or extensions to existing dams to meet demand. Review drought curves to confirm up to date and appropriate. Review drought responses and triggers. Prioritisation of water uses.	Ensure capacity design optimises storage of winter rainfall events.
		Low rainfall will increase demand for water for irrigation and environmental uses.	High	Potential shift in crop types to less water demanding species. Prioritisation of water uses.						Potential requirement for more on-farm winter storage reservoirs or extensions to existing ones. Potential shift in crop types to less water demanding species. Prioritisation of water uses.	
		For reservoirs with secondary purposes, management conflicts can occur when draw down is required for primary function (e.g. recreational use of water supply reservoirs; environmental flow releases).	High	Prioritisation of water uses - think about value of secondary purposes in comparison to primary purpose - potential need for new reservoirs to serve secondary purposes.		Consider prioritising purposes and restricting certain activities during periods of low rainfall.				Potential requirement for more winter storage reservoirs or extensions to existing ones. Prioritisation of water uses - think about value of secondary purposes in comparison to primary purpose.	
		Lower water levels leading to increased concentration of pollutants, lower water quality and higher treatment requirements	High	Prioritisation of water uses. Plan for increased treatment requirements - potential for new techniques.	Increase or amend water treatment facilities.	Potential increase in treatment requirements or alternative treatment requirements.	Increase frequency of water quality monitoring during periods of low rainfall.		Increased use of 'hands off flow' conditions. Seasonal or real-time consenting. More flexible abstraction licensing to take account of real-time catchment conditions (e.g. flows, dissolved oxygen, season). Reduced or variable environmental minimum flow targets. Seasonal changes to water quality targets. Prioritisation of uses, regulation against some uses at certain times.	Potential requirement for more winter storage reservoirs. Prioritisation of water uses. Plan for increased treatment requirements - potential for new techniques.	

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				Long term planning	Remedial Works	Operation & maintenance	Inspection	Decommissioning	Policy & regulation	Long term planning	Design
	High temperature	Increase in water temperature leading to increased vegetation growth and eutrophic conditions. Increased duration and frequency of algal blooms. Reduction in water quality and increase in treatment requirements. Water may not be suitable for some purposes (e.g. environmental releases).	High	Plan for increased vegetation management and treatment requirements.	Design in shading of the water surface e.g. riparian trees.	Shading or covering reservoirs and windbreaks. Potential increase in treatment requirements or alternative treatment requirements. Increased maintenance requirements - more frequent vegetation cutting and removal. Catchment and river management to reduce presence of invasive or fast growing riparian and aquatic species. Restrictions on recreation activities during algal blooms. Use sonic control methods.	Increase frequency of water quality monitoring during periods of high temperature. Monitor for algal types and water quality problems.	May result in earlier decommissioning of some dams.	Seasonal changes to water quality targets. Prioritisation of uses, regulation against some uses at certain times. Catchment management. Review health and safety guidelines regarding algal blooms. Potential need to regulate against some uses at certain times.	Plan for increase vegetation management and treatment requirements.	Design in shading of the water surface e.g. riparian trees.
		Increase in evaporation of stored water, and transpiration from vegetation and soils - lower water levels in reservoirs and less available for use.	Medium	Plan for increased winter storage requirements - may need new reservoirs.	Consider need for cover in summer months. Use riparian trees to increase bankside shade.	Shading or covering reservoirs and windbreaks to reduce evaporation e.g. plastic balls (see Lake Ivanhoe, California). Catchment management to increase vegetation coverage and prevent evaporation from bare soil.			Demand management policies, increased frequency of water restrictions. Reduced or variable environmental minimum flow targets (experience in Victoria, Australia).	Plan for increased winter storage requirements - may need new reservoirs.	Consider need for cover in summer months. Use riparian trees to increase bankside shade.
Recreation and aesthetic	High rainfall	Increased sedimentation and debris during and following flood events - impact on recreational safety, turbidity and aesthetic value.	Medium	Plan for significant maintenance activities such as de-silting; consider knock on issues associated with turbidity.	Retrofitting of sediment control traps or sluice valves.	Increase in maintenance requirements, more frequent debris removal. May require changes in operating approaches to promote sluicing during events and hence reduction in sedimentation. Restrict some recreation activities at certain times.		May result in earlier decommissioning of some dams.	Increased sediment control regulations, land use control in catchments. Review health and safety regulations. May need regulation to restrict some activities at certain times.		
		Increased flows resulting in overtopping of reservoirs. For recreation and aesthetic function, impacts on downstream navigation, downstream water users (caneoists etc).	High		Raise crest or spillway to increase flood storage capacity. Increase spillway volumes.	Amend dam control curves to result in lower normal operating levels during periods/seasons of expected high rainfall. May need to restrict recreation uses during periods of high rainfall.		May result in earlier decommissioning of some dams.	New design regulations relating to peak flows and design storms for storage purposes. May need regulation to restrict some activities at certain times.	Increase capacity of existing dams. Plan for new dams and reservoirs.	Design for more frequent and extreme rainfall events. Increase design capacity to increase flood storage capacity. Design-in resilience to overtopping - increased spillway volumes, erosion protection.
	Low rainfall	Drawdown exposing littoral habitat - impact on biodiversity and loss of aesthetic value.	Medium	Consider alternatives to open water features for aesthetic purpose.	Plant drought tolerant species. Add shading of the water surface e.g. riparian trees.				Change in conservation policy to favour drought tolerant non-native species.	Consider alternatives to open water features for aesthetic purpose.	Plant drought tolerant species. Design in shading of the water surface e.g. riparian trees.

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					Modify bed to allow different habitats at different water levels.						
		Low water levels may prevent certain types of recreation e.g. sailing, or cause access difficulties.	High	Promote non-water based recreation activities e.g. walking, cycling.	Increase storage capacity through crest or spillway raising. Add in shading of the water surface e.g. riparian trees. Modify slipways etc to allow activities during low water.	Promote alternative forms of recreation at certain times of year. Restrictions on recreation at certain times of year.	Determine water depth requirements for different activities and regularly inspect water levels in summer.	May result in earlier decommissioning of some dams.	Review health and safety regulations and regulate to restrict some uses at certain times.	Increase winter storage capacity.	Design reservoirs to include non-water based recreation activities e.g. walking, cycling. Design in shading of the water surface e.g. riparian trees.
		Lower water levels leading to increased concentration of pollutants and lower water quality may reduce aesthetic value and biodiversity. May create health issues if severe.	High	Consider alternatives to open water features for aesthetic purpose.	Increase storage capacity through crest or spillway raising. Introduce drought tolerant species. Add in shading of the water surface e.g. riparian trees.	Promote alternative forms of recreation at certain times of year. Restrict recreation during drought periods. Increase awareness of potential health issues amongst visitors to reservoirs and health professionals.	Increase frequency of water quality monitoring during periods of low rainfall.		Seasonal or real-time consenting. More flexible abstraction licensing to take account of real-time catchment conditions (e.g. flows, dissolved oxygen, season). Reduced or variable environmental minimum flow targets. Seasonal changes to water quality targets.	Consider alternatives to open water features for aesthetic purpose. Plan for increase winter storage capacity.	Design aesthetic reservoirs with drought tolerant species. Design in shading of the water surface e.g. riparian trees. Design reservoirs to include non-water based recreation activities (e.g. walking, cycling) for periods when there are restrictions on water use.
	High temperature	Increase in pests e.g. midges; consider issues associated with mosquitoes in the south.	Medium	Promote non-water based recreation activities e.g. walking, cycling.		Encourage visitors to use insect repellent. Restrict water based activities and promote alternative forms of recreation at certain times of year. Increase awareness of potential health issues amongst visitors to reservoirs and health professionals.	Inspect water temperature throughout the summer to aid forecasting of mosquito pests.		Review health and safety regulations regarding water based recreation in the summer. Regulate to restrict some activities at certain time of year.		Design reservoirs to include non-water based recreation activities e.g. walking, cycling.
		Increase in visitor numbers in shoulder season - extended recreation and tourism season.	High	Review operational staffing and prioritisation of uses at reservoirs.	Construct additional facilities to cater for recreation.	Change operation of recreational facilities.	Monitor visitor numbers throughout the year.	Could be a secondary use for reservoirs that are marked for decommissioning - may prolong their life.			
		Increase in vegetation growth - potential impact on aesthetic value and recreation potential.	Medium	Plan for increased vegetation growth in maintenance regimes.	Plant slow growing, drought resistant species.	Increase frequency of vegetation cutting and clearance.		May result in earlier decommissioning of some dams.	Recognise economic value of recreation at reservoirs.	Plan for reservoirs to increase visitor capacity e.g. increase in facilities, car parks, recreation activities etc. Potential demand for more reservoirs, requires long term planning. Review prioritisation of uses at reservoirs.	Consider recreational needs when designing reservoirs e.g. water depth, steepness of banks, access etc.
		Increase in frequency of algal blooms - blue green algae can be harmful to human or pet health.	High	Promote alternative forms of recreation at certain times of year. Plan for increase vegetation management and treatment requirements.	Design in shading of the water surface e.g. riparian trees.	Use riparian trees to increase bankside shade. Restrict recreation at certain times of year. Increase awareness of potential health issues amongst visitors to	Increase frequency of water quality monitoring during periods of high temperature.		Review conservation policy to favour non-native species. Seasonal changes to water quality targets. Catchment management.	Plan for increased vegetation growth in maintenance regimes.	Plant slow growing, drought resistant species.

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						reservoirs and health professionals.					
		Increased vegetation growth leading to navigation problems for some craft.	Medium	Plan for increased vegetation growth in maintenance regimes.		Increase vegetation management - cutting and removal.			Seasonal changes to water quality targets. Prioritisation of uses, regulation against some uses at certain times. Review health and safety guidelines regarding algal blooms. Land use management. Potential need to regulate against some uses at certain times.	Promote alternative forms of recreation at certain times of year. Plan for increase algal management and treatment requirements.	Design reservoirs to include non-water based recreation activities e.g. walking, cycling. Design in shading of the water surface e.g. riparian trees.
Electricity generation	High rainfall	Damage caused to HEP auxiliary infrastructure (power houses etc) by flooding could be very costly - damage to assets and electricity supply outage.	High	Plan for increasing maintenance costs.	Raise crest or spillway to increase storage capacity. Add in flood defence structures and erosion protection to reduce damage to auxiliary equipment. Increase spillway capacity.	Potential increase in winter maintenance requirements and repairs following high rainfall events. Increased use of flood forecasting tools.	Inspect equipment for flood damage after high rainfall events. Increase inspection for erosion.	May result in earlier decommissioning of some equipment.	Seasonal restriction on size of craft. Land use and catchment management.	Plan for increased vegetation growth in maintenance regimes.	May result in a need to allow for a percentage volume loss for vegetation in design.
		Flood risk may require reduced operating levels, reducing availability or flexibility of power generation.	High	Model changes in rainfall.	Increase return period of design events. Increase height of dam crest or spillway to increase storage. Consider need for downstream flood protection measures. Add in early warning systems.	Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall. Increase use of flood forecasting tools.			Energy demand management, contingency plans to cover potential outages in winter. Look for alternative sources / back up during winter.	Plan for increasing maintenance costs.	Design for more frequent and extreme rainfall events. Design flood defence structures and erosion protection to reduce damage to auxiliary equipment.
		Increase in water available for release during winter.	High	Increase capacity of auxiliary infrastructure to maximise opportunity.	Increase design capacity to increase flood storage capacity.	Move maintenance to summer when water levels are lower and power generation capacity is lower.		May extend the life of reservoir.			Increase return period of design events. Increase design height of dam crest. Consider need for downstream flood protection measures. Include early warning systems in design.
	Low rainfall	Decrease in water available for release or flush during summer.	High	Use winter storage reservoirs to cover deficit in summer. May need more winter storage reservoirs. Look for alternative power sources to supplement summer HEP.	Increase capacity of reservoirs to store increase in winter rainfall.	Timing shutdowns for maintenance during summers when generating capacity is reduced anyway.		May result in earlier decommissioning of some dams.	Potential increase in demand for HEP - more dams and associated infrastructure may be required, planning will need to facilitate this.	Increase number of HEP dams (or run of river generation) to maximise opportunity in winter. Increase capacity of auxiliary infrastructure to maximise opportunity. Increased need for new reservoirs or extensions to existing ones to increase winter storage for use in summer.	Increase design capacity to increase flood storage capacity.
	High temperature	Change in demand for electricity – milder winters reduce power demand, hotter summers increased demand. Opposite to seasonal water	Medium	Use winter storage reservoirs to cover deficit in summer. Look for alternative power sources to supplement summer HEP.	Increase capacity of reservoirs to store increase in winter rainfall.			May extend the life of reservoir.	Demand management, contingency plans to cover potential outages in summer. Agreements with high consumers for	Use winter storage reservoirs to cover deficit in summer. May need more winter storage reservoirs. Look for alternative power sources to	Change design standards to increase capacity of reservoirs to store winter rainfall.

Dam function	Climate variable	Potential impact	Potential vulnerability	Adaptation responses for existing dams					Policy adaptations and adaptations for future dams		
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		availability.							reducing loads. Prioritise water uses.	supplement summer HEP.	
Effluent	High rainfall	Increased flow into impounding reservoirs increases flood risk and risk of overtopping with the resultant downstream pollution risk. Also may require lower operating levels.	High	Increase capacity of existing dams.	Raise crest or spillway to increase flood storage capacity. Increase spillway volumes.	Amend dam control curves to result in lower normal operating levels during periods or seasons of expected high rainfall. Early-warning systems for flooding, real-time information and flood hazard mapping. Increased use of flood forecasting tools.	Downstream pollution monitoring following high rainfall events. Increase inspection for erosion.		Demand management in summer. Agreements with high consumers for reducing loads in summer. Potential increase in winter storage reservoirs required - planning will need to facilitate this.	Use winter storage reservoirs to cover deficit in summer. Look for alternative power sources to supplement summer HEP.	Change design standards to increase capacity in new reservoirs..
	Low rainfall	For impounding reservoirs will result in lower fresh water inflows leading to increased concentration of pollutants and lower water quality.	High	Prioritisation of water uses. Plan for increased treatment requirements - potential for new techniques.	Raise crest or spillway to increase winter storage capacity.	Potential increase in treatment requirements or alternative treatment requirements. Consider timing of releases - may not be able to do so in summer.	Increase frequency of water quality monitoring during periods of low rainfall.		New design regulations relating to peak flows and design storms for storage purposes.	Increase capacity of existing dams.	Design for more frequent and extreme rainfall events. Increase design capacity to increase flood storage capacity. Design-in resilience to overtopping - increased spillway volumes, erosion protection.
		Lower river flows may reduce ability to abstract from and discharge to the environment.	Medium	May increase need for effluent reservoirs to retain water until it can be released to the environment.	Increase capacity of effluent reservoirs to facilitate longer retention times, if required.	May increase the length of time effluent is stored before being released into the environment. Possible increase in treatment requirements.	Water quality monitoring to determine when releases can take place.		Seasonal or real-time consenting. More flexible abstraction licensing to take account of real-time catchment conditions (e.g. flows, dissolved oxygen, season). Reduced or variable environmental minimum flow targets. Seasonal changes to water quality targets. Prioritisation of uses, regulation against some uses at certain times.	Potential requirement for more winter storage reservoirs or extensions to existing ones. Prioritisation of water uses. Plan for increased treatment requirements - potential for new techniques.	Change design standards to increase capacity in new reservoirs.
	High temperature	Increased receiving water temperatures may reduce capacity of environment to accept effluent discharge and may affect ability to treat discharges.	High	May increase need for effluent reservoirs to retain water until it can be released to the environment.	Increase use of treatment prior to discharge. Increase capacity of effluent reservoirs to facilitate longer retention times.	May increase the length of time effluent is stored before being released into the environment. Possible increase in treatment requirements.	Water quality monitoring to determine when releases can take place.		Review consenting standards, consider seasonally variable consenting.	May increase need for effluent reservoirs to retain water until it can be released to the environment. Plan for increased treatment requirements.	Increase use of treatment prior to discharge. Review design rules over capacity and retention time.