A Guide to the Effects of Climate Change in Dams

A. K. HUGHES, Atkins, Epsom, UK
D. HUNT, Atkins, Epsom, UK

SYNOPSIS Atkins has recently completed a document entitled “A Guide to the Effects of Climate Change in Dams” funded by Defra.

This paper will describe the contents of that document which seeks to provide a pragmatic and practical guide to managing the changes to dam structures which might occur due to climate change.

INTRODUCTION

This paper presents the findings of a UK Government (Department of Environment, Food and Rural Affairs) commissioned research project to understand what the likely affects of climate change might be on the maintenance and construction of dams in England and Wales. This involved an evaluation of the existing models and forecasts of climate change, along with the physical impacts that this might have on the construction, maintenance and functioning of dams up to the 2080 horizon. This was used to develop a framework and guidance document for operators, owners and policy makers to evaluate and plan for the impacts that might occur. The project involved:

- A detailed review of the outputs from current climate models and an examination of how well they are able to provide the types of climatic outputs that are required to evaluate how climate change might affect a dam or reservoir. This covered both the climatic parameters (e.g. peak summer rainfall intensity) and the level of certainty involved in the forecasts.
- An examination of the mechanisms through which climate change might affect dams and reservoirs, and the development of an initial risk assessment framework and process for evaluating adaptation measures.
- A number of case studies to examine how the theoretical climate change risks translate into actual, practical risks that are present for dams and reservoirs within England and Wales. The nature of the

Dams: Engineering in a Social and Environmental Context. Thomas Telford, London, 2012

inspection, supervision and planning regimes associated with each of those assets was evaluated to determine how these might have to change in order to adapt to the potential impacts of climate change.

- Production of the final guidance document, which was the key output from the study. The document provides a structured approach whereby asset owners can 'screen' potential impacts on their dams and reservoirs to determine which climate change factors might affect the risk profile, and gives advice on how these risks should be incorporated into the inspection/supervision regime. This is supported by approaches that can be used to develop programmes of measures as operational and capital works become necessary. The guidance also gives information on the forecasts, hydrological modelling approaches and levels of uncertainty (particularly for peak rainfall) that are associated with the latest climate change models.

It should be noted that this paper presents a summary of the investigations that were carried out for the project, and provides a potential, structured approach that can be used by dam owners and operators to evaluate the potential impacts of climate change on their dams and reservoirs. It is intended as research and guidance, and does not represent official U.K. policy or regulation.

BACKGROUND

The project was carried out following an identified need for a comprehensive, up to date review of the impact of climate change on dams and reservoirs in England and Wales, which made use of up to date tools and research such as those that are available from UKCP09. The floods that occurred in England in 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. Because of the wide variation in asset types and nature of the impacts that might occur, the investigations and guidance were intended to be broadly based and comprehensive within the U.K. setting, referring to existing models and climate change research where possible.

APPROACH

The framework for assessing the impact and response to climate change for dams and reservoirs was carried out within the context of **vulnerability-resilience-adaptation** (Willows and Connell 2003). These concepts are widely used in the assessment of the impacts of climate change on infrastructure, and, in this context, can be defined as:

- ***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.
- ***Resilience*** relates to the inherent capability that a particular part of the dam, reservoir and catchment have to incorporate climatic changes without significant negative effects. For example, although a flood storage reservoir may be vulnerable to overtopping during storms with a high return period, and this might represent 'failure' of the dam storage, the embankment itself may not be particularly affected by such events (e.g. if it is a non-erodible or low angle, well grassed homogeneous construction).
- ***Adaptation*** refers to 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.

The framework that was adopted also recognised that dams are large, long asset life structures that are usually designed to be inherently resilient to climatic variation. This resilience is a reflection of both the safety risks that can be associated with dam failure, and the large capital investment that is usually involved in the construction of the dam. The management of water and water resources also has environmental consequences and forms part of a heavily regulated sector. These factors mean that there is a well established regime for managing the design and maintenance of dams in England and Wales, and a number of well established regulatory controls that cover the operation and environmental management of the reservoirs and catchments.

The existence of these regulatory processes has a significant effect on both the vulnerability and resilience of dams and ancillary structures to climate change, and affects the nature of any adaptation systems and measures that can be used. This includes impacts and adaptations that relate to the operation and use of reservoirs. The overall framework for assessment that was used in this project therefore took account of these factors, and had a strong emphasis on understanding how climatic variation interacts with the current construction, operation, supervision, maintenance and regulation of the dam stock within England and Wales. In broad terms the assessment consisted of the following stages:

- **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.

The results of this assessment and the proposed guidance that resulted from the assessment are described below.

CLIMATE CHANGE AND ITS IMPACT ON DAMS AND RESERVOIRS

A number of methods for characterising dams and reservoirs were considered and mapped for the study. This included characterisation according to size, ownership and regional variation. A workshop review with practitioners ultimately concluded that the most appropriate approach was to characterise dams according to their **form** (i.e. physical makeup) and their **function** (i.e. use). This characterisation was 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. The categories of form and function that were applied in the England and Wales setting are describe in **Table 1** below:

Erodible embankments were originally separated according to a number of different types, but given the variability in design it was ultimately decided that they should be considered as a whole and the variability in design would be reflected in the **impact mechanisms**, as described later.

The next stage of the assessment was to determine, on a generic level, the vulnerabilities that the different forms and functions might have to climate change. An initial 'long list' of potential vulnerabilities was derived for each category of form and function based on expert inputs. This was then condensed into a risk weighted short list that could then be used to support the case studies and development of the guidance. The approach that was taken for this shortlisting process is summarised in **Figure 1**. This required the examination of two components of vulnerability, namely **sensitivity** and **exposure:**

- *Sensitivity* refers to the "Scale of response" of a system or component to a change (in this case weather).
- *Exposure* refers to the extent to which the system is subject to the weather or climate variable in question (i.e. how much physical

variability the scale of response causes to the dam/reservoir elements in question).

Table 1. Final Categorisation of Dams and Reservoirs Used in this Study

Categories of Form
Embankment: erodible (clay core, clay blanked, homogeneous etc)
Embankment: non-erodible (concrete/masonry)
Overflow structures (all)
Ancillaries

Categories of Function
Seasonal storage for water supply
Flood retention
Recreation
Fisheries/ecology/wildlife
Hydropower
Other (including effluent storage)

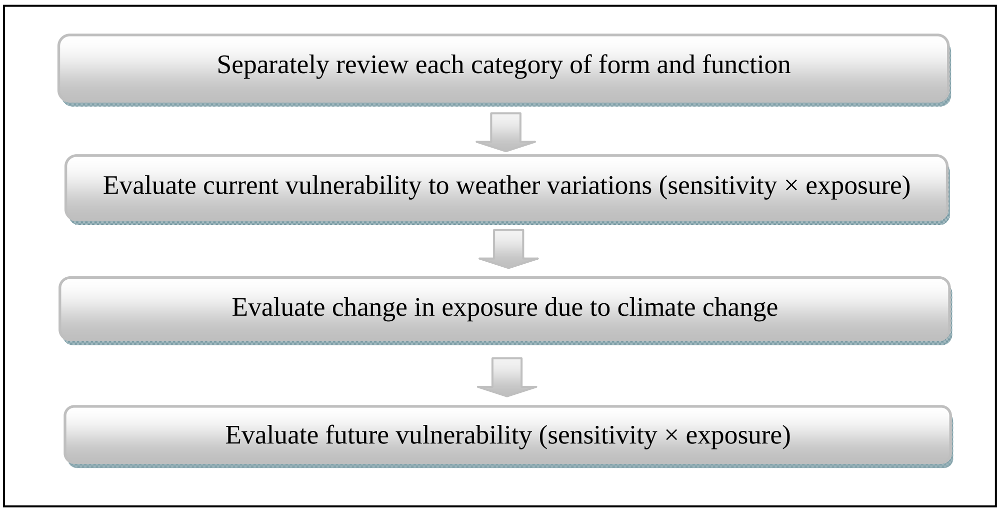

Figure 1. Vulnerability assessment methodology

A total of twelve, interview based case studies were then carried out in order to practically identify how vulnerabilities might present themselves for a variety of dams and reservoirs, and determine how the management regime associated with the reservoir and structures might affect adaptation responses. This produced a wide range of anecdotal evidence and findings that were then used to inform the final guidance document.

The findings on vulnerabilities, management measures and adaptations are too extensive to reproduce within this paper, but included:

- The majority of dams are inherently resilient to climate change, and significant capital works are only likely to be required in the short term for dams where there are existing, known, significant vulnerabilities to weather variation. In the U.K., typical examples might include concerns over spillway capacity/performance, or older earthfill dams that have become damaged by vegetation growth or burrowing animals, and rainfall erosion or desiccation during summer may already be a concern.
- Vulnerability of the embankment to climate change over the longer term is most likely to occur due to combinations of effects that exploit weaknesses in the design, construction or operation of the dam or reservoir. 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 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 role of vegetation is often an important factor in determining the long term vulnerability of this type of dam.
- 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, as well as less apparent issues such increasing water level fluctuation leading to a deterioration in marginal vegetation conditions and hence bankside fishery functions.
- The interaction between the catchment, reservoir and dam is an important factor in the vulnerability of both form and function. For form, the catchment affects direct inputs such as volumetric flows to

spillways, but it also represents a source of debris and erosion that can result in the blockage of spillways, valves and aqueducts, and can cause concentration of runoff erosion or water logging on crests or mitres. Vegetation is again an important factor in the long term risk, as are catchment management practices employed around the dam. The catchment can affect function in a variety of ways that relate to runoff water quality, siltation and water availability. All of these catchment features (including land management/stewardship) are sensitive to climatic variation and hence represent some of the more realistic long terms risks from climate change.

These findings, along with the generic vulnerability assessments, were used to derive a comprehensive list of the climate change factors that needed to be quantified in order to evaluate the vulnerability of dams and reservoirs in England and Wales. **Table 2** provides a list of these factors, along with a high level summary of the potential amount of change involved and the current availability of research to allow quantification of that change. For the study itself, all of the available research and quantified parameters (e.g. ‘plume’ plots of temperature variation) were presented in the form of lookup tables and appendices to allow rapid evaluation of the amount of change involved.

A FRAMEWORK FOR MANAGING THE IMPACT OF CLIMATE CHANGE ON DAMS AND RESERVOIRS

Because it relies largely on factors such as existing weaknesses in the design, the nature of the individual catchment and the type and complexity of the management regime, the vulnerability of dam form and function is highly site specific and needs to be addressed on an individual basis. However, the study did show that a relatively simple, staged, risk based approach can be used to screen and assess climate change impacts for any type of dam asset. For England and Wales this was designed to fit in with the existing Section 10 and Section 12 supervision and inspection processes that are carried out under the Reservoirs Act 1975, and fit in with the asset management processes used by Water Undertakers and the Environment Agency to manage the form and function of their assets.

The framework that was developed can be used to evaluate impacts and associated adaptations for existing dams, and the guidance document included policy adaptations and design suggestions for potential new dam stock. Because recommendations for new dams were largely derived from the assessment of the existing dam stock, the rest of this paper will concentrate on the framework that was developed for maintaining existing dams.

Table 2: Summary of Relevant Climate Change Factors

Climate change variable or effect required for evaluation	**Level of climatic change predicted***	**Adequacy of Current Predictions/Evaluation Methods**
Rainfall – daily maximum	Significant increase	Reasonable through UKCP09 (see Murphy et al., 2009)
Rainfall – storm return period	Winter: significant (more frequent events) Summer: not significant	Some studies carried out; information probably adequate
Rainfall - average	Significant (winter and summer)	Reasonable through UKCP09
Flows	Winter: significant increase Summer: significant decrease	Reasonable through UKCP09 and standard hydrological approaches
Temperature	Significant increase	Reasonable through UKCP09
Snowfall	Significant decrease	Reasonable through UKCP09
Wind	Not significant	N/A
Potential Evapotranspiration (PET)	Significant increase	Reasonable through UKCP09 and standard hydrological approaches
Groundwater levels	Variable (according to area/aquifer)	Highly problematic unless groundwater models are available
Water demand	Significant increase	Reasonable through Water Resource Management Plan background guidance.
Water quality	Variable, but generally significant	Relatively poor; outline guidance provided through this project*
Vegetation growth rates/growing season	Significant increase	Reasonable research available relating to Growing Degree Days (GDD)
Demand for heating and cooling (hydropower energy)	Winter decrease, summer increase – overall impact is variable but may not be significant	Reasonable based on UKCP09 and number of 'heating degree days' (HDD) and 'cooling degree days' (CDD)
Climatic stress on vegetation (trees, peat, grasses)	Potentially significant (change in species mix)	Reasonable research available; particularly for grasses and trees (through Forestry Commission)
Pests/invasive species	Potentially significant increase	Highly species specific
Stress and disease risk for humans	Potentially significant	Reasonable research available
Fish/aquatic parasites	Variable; significant for some species	None – possibly use changes in growing season as an indicator

** Based on a variety of papers and information. Recent examples are provided in the references list.*

Figure 2 gives an overview of the evaluation framework for existing dams. There are five main points to note about the process:

1. Dam owners and operators will often have complex models and corporate functions that already exist for the planning, operation and maintenance of dam assets. For example, in the case of public water supply dams there will be an existing statutory inspection regime, an asset management planning process (currently carried out on a 5-yearly cycle), a water resource management planning process (also a 5-yearly cycle), operational control curves and possible hydraulic and water quality models for the reservoir and dam operation. Multiple stakeholders may be involved in operation, catchment management or day to day surveillance of the dam and reservoir. These existing processes and stakeholders represent the ***decision context*** that the assessment will need to be carried out in. Because climate change impacts will normally result from a combination of factors it is important that this context is broadly understood before the assessment framework is implemented.

2. Prior to the main assessments for form and function, it is recommended that a review of ***catchment vulnerability*** is carried out to establish the main catchment features (i.e. soils, vegetation, catch waters etc) and evaluate their vulnerability to climatic variation. This will affect both form and function.

3. ***Co-ordination*** between form and function is essential, as there are likely to be feedback mechanisms between the way that the dam itself is maintained and operated, and the way that the reservoir and catchment are used and operated. Within England and Wales it is likely that the Supervising Engineer will be most suitable for this co-ordination role. It is not necessary to carry out assessments for form and function at the same time; the important point is to ensure that findings are co-ordinated once the assessments have been carried out.

4. ***Recommendations for adaptation*** should be made within the existing management framework for the asset. Usually these will involve relatively minor modifications to existing operational or maintenance practices (e.g. vegetation management), and any capital works should be promoted through established mechanisms to avoid duplications or conflicts with other asset management activities.

5. The ***frequency of update*** for assessment is risk dependent, but should generally range from once every 5 years for high risk assets to once every 20 years (or upon major change of circumstances) for low/negligible risk assets.

The recommended methods for technical assessment of both form and function rely on a risk based approach that is intended to allow rapid screening of assets that are less vulnerable, and concentrate on those potential impacts that could have the largest impact on integrity or maintenance costs.

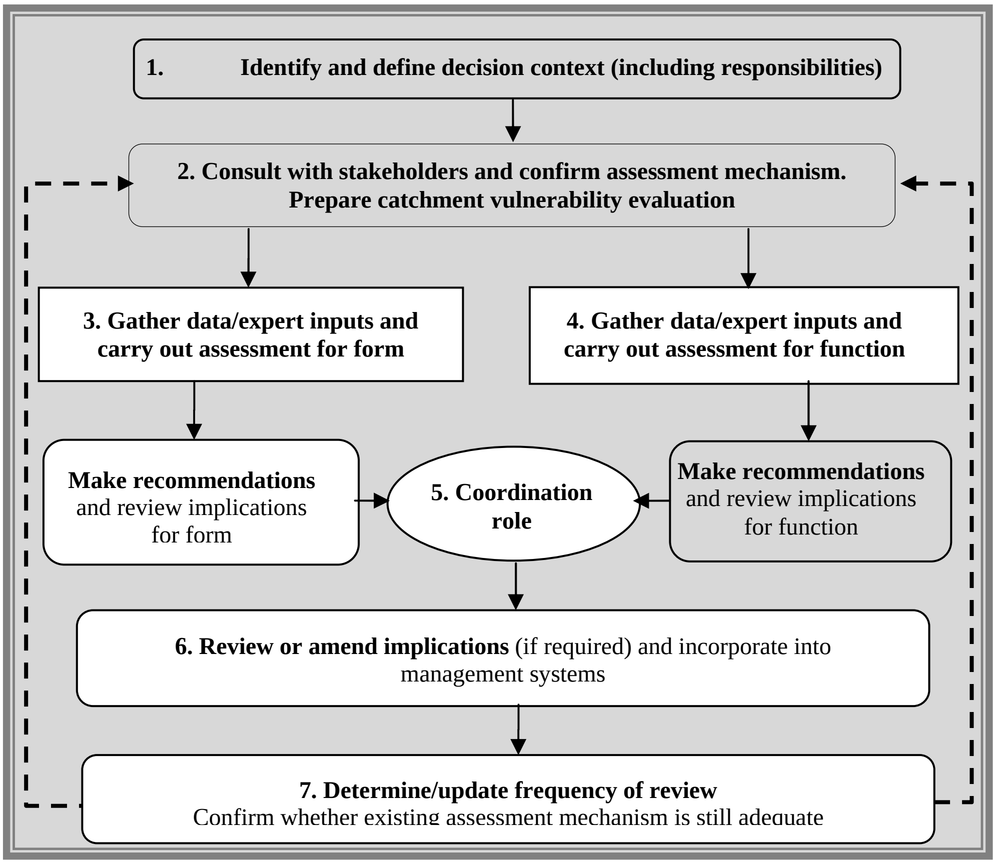

Figure 2. Simplified Overview of the Evaluation and Adaptation Framework

The approach differs slightly between form and function, as follows:

- The evaluation framework for form uses ***failure modes*** and associated ***impact mechanisms*** to assess risk, rather than considering the impact from individual effects such as rainfall or temperature. An overview of the evaluation framework is shown in **Figure 3.**
- The process for function is similar to that show **in Figure 3**, but 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.

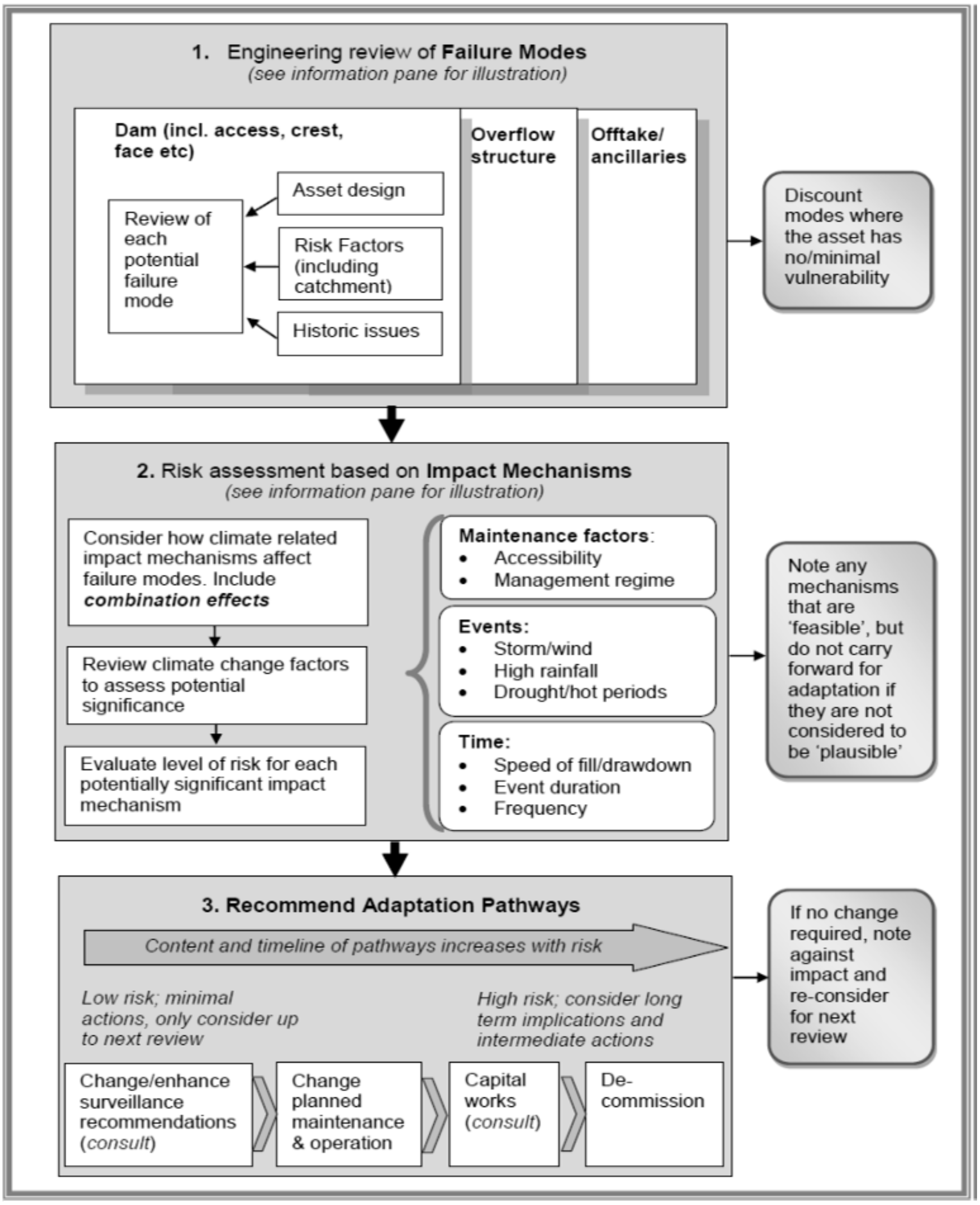

Figure 3. Assessment Framework for Form

The concept of ***failure modes*** and ***impact mechanisms*** is best illustrated through example. **Figure 4** shows one of the information panes that was developed to show how the impact mechanisms and risks of failure can be evaluated for one failure mode; namely the risk of increased erosion on the upstream face of an erodible embankment. This shows how each failure mode can be linked through to specific impact mechanisms and relevant climate change guidance in order to carry out the risk assessment.

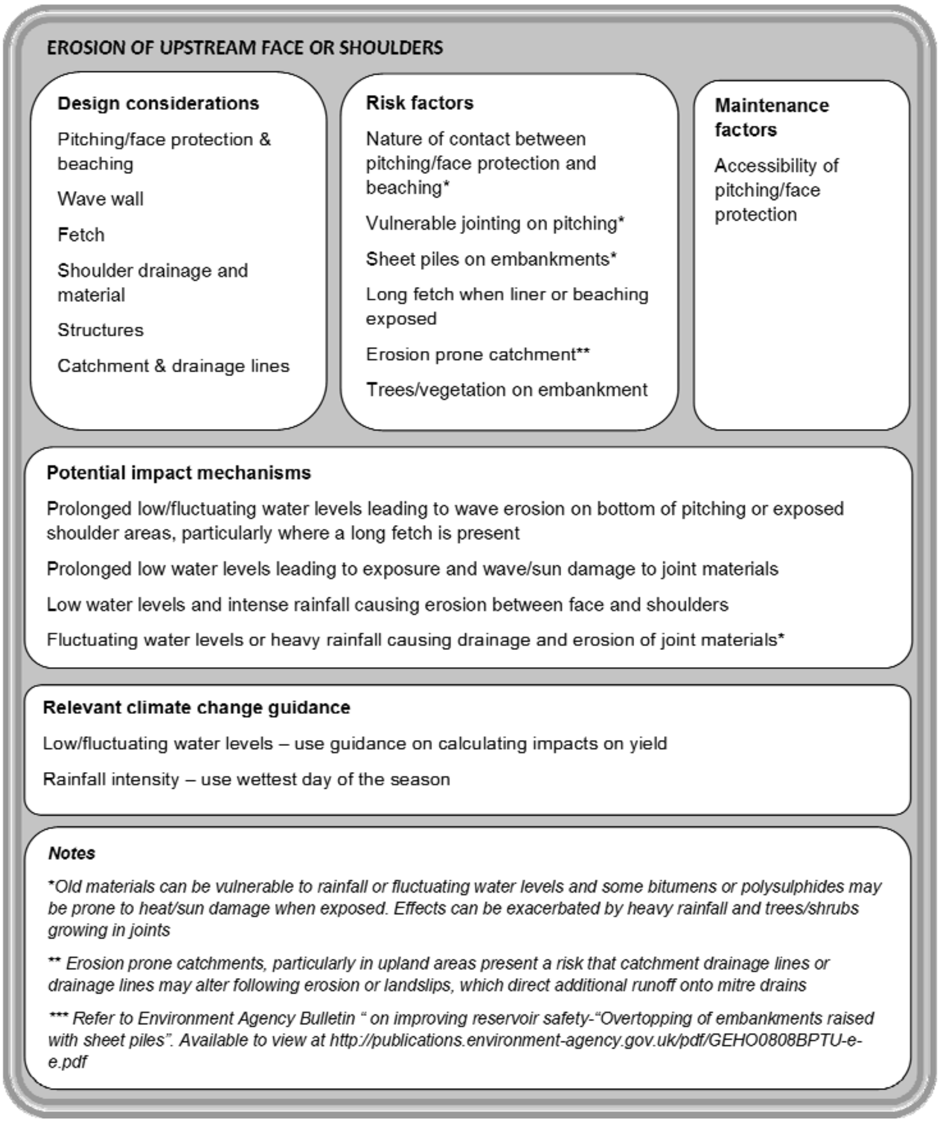

Figure 4. Example 'Information Pane' for Failure Modes Involving Erosion of Upstream Face or Shoulders

This assessment framework, as shown in **Figure 3** was further refined into a pro-forma approach that can be used during a supervision visit to allow a rapid evaluation of the level of risk associated with each potential failure mode. This pro-forma provides an initial screening to determine whether the mode is potentially significant or relevant, followed by a standard format risk assessment (risk = likelihood * consequence) that uses the information panes, lookup tables for climate change effects and the associated appendices contained within the guidance document. In many cases this approach will be sufficient to evaluate the risks and impacts of climate change. For those dams and reservoirs where high significance risks are identified, then further evaluations such as hydrological/hydraulic modelling, water quality modelling etc can be used to better quantify timescales and significance for the particular failure modes and impact mechanisms involved.

Adaptation measures were considered as part of the study, but are too extensive to detail here. However, the general concept was to derive adaptation ***pathways*** that account for risk severity and the timescales involved in risk materialisation. These pathways form plans for the asset that can be incorporated into existing management regimes. In most cases an adaptation pathway will tend to involve a hierarchy of:

- Changes to surveillance/monitoring
- Modification of operation and planned maintenance regimes
- Capital works and major re-active maintenance
- Decommissioning or change of use.

Where required, capital works and decommissioning/change of use will generally only occur in the longer term and can be better quantified through surveillance/monitoring during the initial years of the plan. The recommended approaches for assessing adaptation pathways for form and function are described in **Table 3**.

Table 3. Approach to assessing adaptation pathways

Evaluation	**Form**	**Function**
Stage 1	Review the risk factors and the impact mechanisms involved	Review the severity of the constraints and the timescales over which impacts might occur
Stage 2	Evaluate the level of uncertainty and risk to determine what additional monitoring/surveillance is needed	Determine if any additional monitoring is required to understand the more significant constraints before they become problematic
Stage 3	Consider what the ultimate impact might be without management changes and determine how this could be deferred through maintenance/operation	Determine what pro-active maintenance or changes in operation could be implemented to defer or prevent impacts
Stage 4	Evaluate risks and timetables involved in capital works	Consider potential capital works or changes in function that may be required

CONCLUSIONS

By examining the impact of climate on dams and reservoir in a structured, evidence based manner it has been possible to evaluate the broad and complex interactions that might occur as climate changes in the future.

Although some generic conclusions can be drawn (e.g. that erodible dams such as earthfill structures are most likely to be affected by climate change), the complexity and uniqueness of each dam and reservoir means that it is impossible to be prescriptive about the impacts on a generic basis. However it was possible to derive appropriate guidance notes and provide a framework for assessment that could be used to evaluate impacts for all types of dams and reservoirs.

Dams and reservoirs were generally found to be relatively resilient to climate change, and impacts are most likely occur through mechanisms that are already known about or suspected by practitioners that are familiar with the asset. Understanding the effect that current variations in climate have on the dam and reservoir therefore provides a good basis for evaluating the impact that future changes in climate might lead to. The most appropriate approach to evaluating future impacts was found to be one that considers the *form* (the physical structure of the dam and ancillaries) and *function* (the operational and secondary uses) of the dam and reservoir as separate, but interlinked categories of the overall asset. Impacts on form were best evaluated by considering the *failure modes* and *impact mechanisms* that might result from climate change, rather than simply considering changes in climate and the direct effects that these might have on the dam structure. Similarly, impacts on function were best evaluated by considering the *constraints* and *tipping points* that might cause the current operation and use of the dam/reservoir to be affected by climatic variations. The vulnerability of the catchment to climate change was found to be significant to both form and function and understanding this vulnerability forms an important part of the assessment process.

The range of measures that can be used to adapt dams and reservoirs to climate change were found to be similarly varied, but again a structured approach was developed that used the impact mechanisms and constraints to determine which adaptation measures would be suitable for the asset. These can be structured into plans (or *pathways)* that fit in with existing asset management processes and proportionally increase in significance as the risks from climate change increase for the asset.

One of the key conclusions of the study was that the risk assessment and evaluation of adaptation measures can be carried out rapidly and efficiently using a guidance document and pro-forma approach, in a way that is designed to fit in with the existing management processes. In most cases the majority of the risks can be rapidly screened out, and the remainder can be evaluated to an acceptable level using lookup tables, outline guidance and hydrological information provided through national level reports or existing studies (e.g. Water Resource Management Plans). In the shorter term, adaptation responses will generally only involve changes in monitoring and pro-active maintenance, unless there is significant, known vulnerability to weather variation.

REFERENCES

Collier, C.G. 2009. *On the relationship between Probable Maximum Precipitation (PMP), risk analysis and the impacts of climate change to reservoir safety*, FREE Science Paper No.2, NERC, Swindon. 11pp.

Collinson, N. and Sparks, T. 2005. *Nature's calendar – 2004 results from the UK Phenology Network*. British Wildlife, 16 (4): 251-256.

Darch, G.J.C. 2010. *Climate change and future flooding in the UK. PhD Thesis, Climatic Research Unit and Tyndall Centre for Climate Change Research, School of Environmental Sciences*, University of East Anglia.

Defra 2010. *What are non-native species?* Available at http://www.defra.gov.uk/wildlife-pets/wildlife/management/non-native/about.htm, last accessed 14/02/2011

Defra. 2006. *Supplementary Note to Operating Authorities – Climate Change Impacts, October 2006. Flood and Coastal Defence Appraisal Guidance*, FCDPAG3 Economic Appraisal. Defra, London.

Defra. 2009. *West Nile Virus.* Available at http://www.defra.gov.uk/foodfarm/farmanimal/diseases/atoz/westnilevirus/ [Accessed 8/2/11].

Downing, T.E, Butterfield, R.E., Edmonds, B., Knox, J.W., Moss, S., Piper, B.S. and Weatherhead, E.K. (and the CCDeW project team) (2003). *Climate Change and the Demand for Water, Research Report.* Stockholm Environment Institute Oxford Office, Oxford.

Environment Agency 2010. *Managing invasive non-native plants*. Environment Agency, Bristol

Hacker, J.N., Belcher, S.E. and Connell, R.K. 2005. *Beating the Heat: keeping UK buildings cool in a warming climate.* UKCIP Briefing Report. UKCIP, Oxford.

Model predictions of extreme rainfall for a changing climate, Q. J. R. Meteorol. Soc., 129: 1607-1621.

Kendon, E. and Clark, R. 2008. *Reliability of future changes in heavy rainfall over the UK.* In: BHS Tenth National Hydrology Symposium. Exeter, 2008. London, British Hydrological Society.

Kovats, R. S. and Hajat, S. 2007. *Health stress and public health: a critical review*, Annu. Rev. Public Health, 29:9: 9.1–9.15.

Kuhn, K.G., Campbell-Lendrum, D.H., Armstrong, B. And Davies, C.R. 2003. *Malaria in Britain: Past, present and future*, PNAS, 100(17): 9997-10001.

Morrison, J. L. and Morecroft, M. D. (eds) 2006. P*lant Growth and Climate Change*. Wiley-Blackwell

Murph, J. M. et al 2009. *UK Climate Projections Science Report. Climate change projections.* Met Office Hadley Centre, Exeter.

Parrott, D. Sugoto, R, Baker, R., Cannon, R., Eyre, D., Hill, M., Wagner, M., Preston, C., Roy, H., Beckmann, B., Copp, G.H., Edmonds, N., Ellis, J., Laing, I., Britton, R., Gozlan, R.E. and Mumford, J. 2009. *Horizon scanning for new invasive non-native animal species in England*. Natural England Commissioned Report NECR 009, Natural England, Peterborough

Rahel, F.J. and Olden, J.D. 2008. *Assessing the effects of climate change on aquatic invasive species.* Conservation Biology, 22 (3), 521 – 533

Ray, D., Morison, J. and Broadmeadow, M. September 2010. *Climate change: impacts and adaptation in England's woodlands.* Forestry Commission Research Note 201.

Reynard, N.S., Crooks, S., Kay, A.L. and Prudhomme, C. 2009. *Regionalised impacts of climate change on flood flows.* RandD Technical Report FD2020/TR. Defra, London.

Sanderson, M, 2010. *Changes in the frequency of extreme rainfall events for selected towns and cities*. Report to Ofwat, published on Ofwat website.

Soverow, J.E. Wellenius, G.A., Fisman, D.N. and Mittleman, M.A. 2009. *Infectious disease in a warming world: How weather influenced West Nile Virus in the United States (2001-2005),* Environmental Health Perspectives, 117(7): 1049-1052

UKWIR. 2007. *Effects of Climate Change on River Flows and Groundwater Recharge: Guidelines for Resource Assessment and UKWIR06 Scenarios.* Report Ref. No. 06/CL/04/8. UK Water Industry Research, London.

UKWIR. 2009. *Assessment of the Significance to Water Resource Management Plans of the UK Climate Projections 2009.* UKWIR. Report 09/CL/04/11. United Kingdom Water Industry Research, London.

Walmsley, C.A., Smithers, R.J., Berry, P.M., Harley, M., Stevenson, M.J., Catchpole, R. (eds.). 2007. MONARCH – *Modelling Natural Resource Responses to Climate Change – a synthesis for biodiversity conservation*. UKCIP, Oxford.

Willows, R. and Connell, R. (eds) 2003. *Climate adaptation: risk, uncertainty and decision-making.* UKCIP Technical Report. UKCIP, Oxford