In Association with
CEH Wallingford

**DEFRA**

# Climate Change Impacts on the Safety of British Reservoirs

Research Contract

Final Report

BWA 20123 January 2002

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Our ref BWA 20123/JWF/WRD Your ref WS 194/2/24

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23 January 2002

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Dear Mr Bates

**Research Contract**
**Climate Change Impacts on the Safety of British Reservoirs**

We refer to the Department's letter of 27 April 1999, reference Area 1-1, accepting our tender for the above named project.

We have pleasure in submitting our Final Report on Climate Change Impacts on the Safety of British Reservoirs.

Yours sincerely

J W Findlay
Technical Director

jr

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## Executive Summary


The Department of the Environment, Transport and the Regions (DETR) now DEFRA, through their reservoir safety research programme, commissioned Babtie Group (BG) in association with the Institute of Hydrology (now CEH Wallingford) to examine the impact on safety of projected changes in magnitude of extreme events, and to consider the scale of precipitation and gale events that might cause risk of exceeding the capacity of existing dams.

Climate change data were obtained from the UKCIP98 climate scenarios that are based upon the output of the Hadley Centre Global Climate Model (HadCM2) that has a spatial resolution of approximately 300km. However the accompanying UKCIP98 10km resolution "Unintelligent downscaling" data were used in this study to supply a guide to the location specific analysis. This dataset is based upon the addition of large-scale interpolated changes to the 10km gridded 1961-1990 baseline climatology. Although the downscaling provides extra precision it does not improve the accuracy of the projections, as this relies on the large-scale climate changes generated by the global climate model.

There are considerable uncertainties in the application of current climate change scenarios. Confidence in the projections diminishes as the focus becomes more event specific, decreasing through regional monthly rainfall averages, and leading to low confidence in projections of storm event characteristics. There is thus a difficulty in downscaling Global Climate Model outputs and this presents problems in addressing storm driven impacts such as those required for reservoir safety. Care is needed in interpreting such predictions.

The general trends emerging from the UKCIP98 work suggest moderate increases to annual rainfall across the country, but with the north becoming relatively wetter than the south. Distinct seasonal differences with large increases to Autumn and Winter rainfall and a contrast between spring and particularly summer rainfalls that are projected to reduce in the south east and slightly increase in the north west. Average wind speeds are projected to change little with the exception of increases in the autumn. Very limited quantitative information is supplied describing either daily or event based climatology. Therefore, in absence of guidance on how extreme event rainfalls and winds are likely to change in the future, projected changes in monthly rainfall and wind were used as a surrogates. While other options were considered, at the present time this is the most suitable approach that can be adopted.

The research project had to consider how these changes might affect reservoirs. Essentially, rainfall intensity, floods and winds impact on the available freeboard of a dam. This, in turn, is influenced by overflow discharge capacity.

The approach followed was to assess the surcharge sensitivity of example reservoirs to incremental changes in the climatic factors affecting the design estimation of total surcharge. Fourteen example reservoirs were selected such that their design, hydro-climatic and geographical characteristics were reasonably representative of the characteristics of the overall population of British dams. However these reservoirs should be regarded as semi-synthetic i.e. while based on actual reservoirs they were not precise replicas thus preserving a degree of anonymity. The surcharge estimation procedure outlined in the third edition of the Floods and Reservoir Safety guide was followed. The key climatic attributes incrementally changed were: i) storm rainfall depth (in the estimation of flood surcharge), and ii) wind speed (in the estimation of wave surcharge). Other related climatic factors, such as storm profile, snowmelt and wind direction, were considered but until more is known about the likely effect of climate change on these it was considered premature to adjust them. This sensitivity was set in the context of climate change projections by overlaying the sensitivity charts with site specific envelopes of climate change scenarios. This work produced charts of sensitivity for both summer and winter events.

Based on the results of this work, the study has produced the following generalised findings:

- Most reservoirs show approximately +5% sensitivity in total surcharge level to the joint worst case projection of storm rainfall depth and windspeed changes for the 2050s time horizon. (Some show a slightly greater response). No regional pattern of risk to reservoirs was evident from the findings.

  This scale of response is considered to be similar to the error range of flood routing and wave run-up calculations due to the various input parameters, and therefore does not demonstrate particular sensitivity of UK reservoirs to climate change at this time.

- Large uncertainties are particularly inherent in the climate change understanding of extreme storm events. These findings should therefore be viewed as providing only a provisional guide. However the sensitivity analysis may remain valuable to assess the implications of future improved climate change projections.

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## 1 Introduction

The Department of the Environment, Transport and the Regions (DETR) now the Department for the Environment, Food & Rural Affairs (DEFRA), through their reservoir safety research programme commissioned a study to examine the impact of predicted changes in frequency of extreme events due to climate change and to consider the scale of rainfall and gale events that might cause risk of exceeding the capacity of existing dams.

Based on a proposal dated February 1999, Babtie Group (BG) in association with the Institute of Hydrology (now CEH Wallingford) was awarded the research study.

Access was given to research data from the UK Climate Impacts Programme (UKCIP) for this study (as made available on the UKCIP98 CD-Rom to research groups). This resulted in the production of scatter diagrams giving envelopes of potential change in wind and rain for the four UKCIP98 scenarios on a site-specific basis.

The research proposal was further developed during the course of the study and presented to DEFRA in a series of formal and informal progress meetings.

The work has also been presented, at various stages, to the reservoir safety industry, principally at the British Dam Society Conference in June 2000. Discussion of the work was encouraged at these forums and any comments have been noted.

The methodology used for the research was to plot the predicted sensitivity of total surcharge to incremental (percentage) changes in rainfall depth and windspeed for a number of representative reservoirs. The predictions were made using multiple Micro FSR software runs following the guidance given in "Floods and Reservoir Safety, 3rd Edition" (Institution of Civil Engineers, 1996). For PMF events this was done for both summer and winter conditions.

The work is presented in this report as advice to DEFRA to inform their reaction to climate change impacts on reservoir safety. This includes the principal hard output of 28 sensitivity charts for representative UK reservoirs that demonstrate the impact of the postulated climate change scenarios on reservoir surcharge levels.

This work comes with a cautionary note in respect of the climate change scenarios postulated and in particular the regional impact envelopes portrayed as rectangular zones in this study. These are not well defined at their outer limits and should be regarded as having fuzzy edges.

It is important to acknowledge the contribution of other organisations whose work has been made available through DEFRA for this project.

- BRE - Dams Database
- UKCIP - Climate Change Scenarios

The report deals firstly with Reservoir Safety Issues to frame the background to the impact of rainfall (floods) and wind (waves). This puts the subsequent sections on Methodologies and Climate Change in context.

# 2 Review of Reservoir Safety Issues

## 2.1 Summary of Present Reservoir Standards and Regulatory Conditions

The response of a reservoir and dam to increased extreme combinations of rainfall and winds can be expressed as increases in still water flood rise and wave run-up.

In terms of flood and wave surcharge the safety of embankment dams is judged by the adequacy of freeboard. The responsibility for engineering aspects of the safety of dams and reservoirs for the protection of the public is placed both on individual engineers (appointed by the government to panel lists), and on reservoir owners.

Panel Engineers are provided with guidance on acceptable freeboard but ultimately have to make independent judgements on adequacy. No mandatory standards are imposed by Government. However the following guidance is given in Chapter 2 of the third edition of "Floods and Reservoir Safety, (Institution of Civil Engineers, 1996). " (The Floods and Reservoir Safety publication is henceforth referred to as FRS in this report).

"For fill embankment dams, the elevation of the top of the dam will be governed by one of two conditions, the first being that the flood surcharge level should not exceed the top of the dam, normally the crest roadway level. If the flood peak is particularly prolonged the flood surcharge level may have to be lower still to avoid harmful leakage through the road foundations above the dam core. The second condition is that the total surcharge must not overtop or pass through or round a structurally sound wave wall to an extent that might lead to a breach of the dam. If there is no wave wall, the top of the dam has to be high enough to contain the total surcharge (unless the dam is assessed to be capable of withstanding limited overtopping)." (Institution of Civil Engineers, 1996).

The factors that an engineer will take into account in deciding adequacy are as follows:

- The appropriate flood category
- The attenuation response of the reservoir
- Ultimate capacity and blockage potential of overflow
- Nature of upstream slope
- Presence of wave wall
- Overall margin of freeboard
- Ability to resist overtopping

It is normally accepted that a high hazard dam should have an absolute minimum freeboard of 600mm with lesser values for lower hazards. It is also accepted that some dams can tolerate overtopping to some degree but this is normally allowed for by de-rating the design flood/waves. The range of freeboards recognised as acceptable is therefore large, ranging from500mm to 5000mm or more. Flood rise and wave run-up allowances vary tremendously across the range of UK reservoirs and cannot be effectively summarised. Determination of these is subjective and often calls for/allows for considerable interpolation. Erosion of present margins by future increases is thus difficult to express in simple terms.

## 2.2 Methodologies Currently Used to Predict the Impact of Extreme Events upon Reservoir Safety

The generally accepted method for determining freeboard adequacy is to follow that described in FRS. The approach combines predictions of design flood inflow and design wave height together with the physical characteristics of the specific dam.

Flood estimates in support of reservoir safety should be based on a rainfall-runoff approach. The only rainfall-runoff method so far generalised for application throughout the UK is the FSR rainfall-runoff method (NERC, 1975). This method has been restated with some revisions to input parameter values but no change to the structure of the model in the recently released Flood Estimation Handbook (Houghton-Carr, 1999). The implications of the Flood Estimation Handbook to reservoir flood studies are further discussed in Appendix D.

The highest hazard dams with no reliable overtopping resistance have to be assessed against the Probable Maximum Flood (PMF). This is a notional worst case event based on Probable Maximum Precipitation (PMP) and a series of interpreted catchment characteristics judged to be unprecedented. Current estimates of PMP assume a stationary climate. If this is no longer observed then the theoretical “upper bound” to rainfall may be changed.

For the UK, the PMF calculated by the Flood Studies Report (FSR, 1975) nearly always results in a flood event greater than the 1:10,000 year event.

The PMF inflow for a given catchment, routed through a reservoir gives the maximum flood rise to be used in assessing freeboard. The flood rise calculation is heavily dependent on the parameters used for the overflow head/discharge relationship.

Lower hazard categories of dam are assessed against more frequent (and lower) flood flows. These range from 1:150 year floods for remote dams with no infrastructure downstream, to 1:10,000 year floods for dams where loss of life is circumstantial or where the dam can withstand some overtopping. This approach reflects the concept of tolerable risk in relation to the safety of the public. Implicit in this approach is the acceptance that a low hazard dam will probably fail if exposed to a flood event in excess of the recommended standard.

In terms of this brief the lowest category might be regarded as academic and of limited importance.

### 2.3 Climate Change

The UK is taking a leading role in addressing the threat of climate change. The effects of climate change, which may be altering the pattern of rainfall and evaporation around the world, are possibly apparent already in some parts of the United Kingdom, for example in the apparent increased incidence of flood events.

General findings of the UK Climate Impacts Programme (Hulme & Jenkins, 1998) suggest that changes in mean climate will also be accompanied by changes in the frequency of extreme events. Intense daily precipitation events are expected to become more frequent, especially in winter, but there is little change predicted in the return periods for daily-mean wind extremes. Changes in storminess are also expected to be quite modest, although summer gales become a little more frequent as do very severe winter gales. These modelled changes in wind regimes in the UK are not very robust and experiments with different climate models yield different results.

Projected changes to extreme rainfall and wind speed characteristics implies that there may be an impact on reservoir safety through the erosion of current safety margins, particularly freeboard. This study has attempted to put in context the sensitivity of UK dams to projected resulting changes to floods and waves.

### 2.4 Consideration of Risk in Dam Safety Evaluation

#### 2.4.1 Risk Issues

Risks are present in every human activity and this study is related to the risk associated with hazards arising from events in the environment external to dams: floods and winds. The notion of risk is inseparable from the ideas of probability and uncertainty. We can be certain that a dam will be subjected to wave action in its lifetime, it will almost certainly spill on an annual basis but we have no real idea whether it will overtop due to wind and waves, even under present climatic conditions.

Risk is therefore a recognition of future uncertainty and from a dam safety point of view, the possibility of disaster or loss.

Some consequences are so severe that they should not be tolerated under any circumstances, for example, failure of a nuclear power station, and therefore very low probabilities (risks) have to be demonstrated. Other consequences are so insignificant that they can be tolerated without further justification, for example, being caught in the rain.

Consequences can be severe and risks tolerable (air crashes) or severe and intolerable eg gas main explosions, although the probabilities may be similar. Dams and reservoirs come into the category of potentially serious consequences with little public perception that there is a risk.

Individual choice and consequences also come into the decision making/tolerability equation. An individual can choose not to fly but a community cannot move out of the flood route from a dam.

Current public perception is that dams are low risk structures and current reservoir safety guidelines seek to maintain this status for high hazard structures.

#### 2.4.2 Hazard Awareness

Hazard is the condition in which there is potential injury, loss or damage. The hazard in the case of dams is the potential energy of the stored water. The consequences are flooding damage, destruction of infrastructure, injury and loss of life plus associated costs

All dams represent a hazard whereas not all are at risk. The safety evaluation of existing dams depends on factors which are specific and real, such as overtopping, material damage and deterioration.

### 2.4.3 Issues to be addressed

The events of concern in this report are extreme floods and waves and how these might be affected by climate change. Reservoir safety guidance currently checks design adequacy against rare events of notional return period (probability). While climate change scenarios suggest how some of the basic climatic inputs to floods and waves might change, there is no firm projection of how the probability of particular events in the future might change. Any detailed risk-based comparison is therefore impossible to present at this time.

In considering the safety of reservoirs the approach therefore has been to look at the sensitivity of reservoirs to finite changes in the effect of increased floods and waves i.e. the sensitivity of dam freeboard to increased total surcharge.

## 3. Methodologies

### 3.1 Introduction

Assessing the possible influence of climate change on extreme flood and flood related events is at present made very difficult by the limited understanding available of how climate change may be expected to affect extreme storm characteristics. Guidance given in the UK Climate Impacts Programme Scientific Report[1] (Hulme and Jenkins, 1998) is mainly restricted to non-quantitative assertions that the mean climate will be accompanied by changes in frequency of extreme events. Intense daily precipitation events are suggested to become more frequent; summer gales and winter very severe gales are both suggested to become a little more frequent. Within neither the UKCIP98 report nor the accompanying CD-ROM is there sufficient information and guidance to permit the characteristics of future storms to be modelled with much certainty.

The approach followed in this report is therefore to perform a sensitivity analysis upon the predicted total surcharge levels of a number of representative reservoir spillways to incremental changes in the design magnitudes of those climatic factors used in the prediction of total surcharge. Their responsiveness in terms of freeboard adequacy is then set within the context of our present, albeit incomplete, understanding of climate change.

### 3.2 Selection of representative reservoirs

A dam’s design ability to accommodate flood surcharge conditions is dependent on both the hydro-climatic characteristics of the reservoir\catchment system and on the structural design of the dam. The hydro-climatic conditions include reservoir and catchment size; hydrological responsiveness of catchment; and the rainfall, snow and wind (extreme) characteristics of the catchment. Structural design features include type of spillway, type of embankment, wave wall design, and reservoir risk category. This dependency on numerous variables renders the selection of a set of ‘typical’ British reservoirs awkward.

To more clearly understand the population characteristics of British reservoirs the information held on the BRE Dams Database[2] was reviewed. (A graphical summary of the following pertinent characteristics are found in Appendix C: spillway type; dam type; dam risk category; reservoir surface area; and age of construction). The BRE information

[1] The UK Climate Impacts Programme Technical Report No.1 (Hulme and Jenkins, 1998) presently provides the most up to date and readily available climate change projections for the UK. The projections for the twenty-first century draw upon the series of climate modelling experiments performed by the Hadley Centre using their HadCM2 model.
[2] BRE Dams Database – draft version provided by British Research Establishment Ltd.

was used to help guide the selection of a subset of reservoirs that could be described as being broadly representative of the general overall population.

The principal criteria used in the final selection process were:

- The targeting of earthfill embankment dams, which are more at risk to changes in flood rise than concrete or masonry types.
- The targeting of uncontrolled (non-gated) spillway dams, plus the selection of a small number of bellmouth spillways.
- A bias towards category A high hazard dams.
- The need to select from a range of reservoir sizes. (Although the numbers of small reservoirs dominate the population (Appendix C), the flood response characteristics of large reservoirs are different and require investigation. The consequences associated with a large dam failing are also potentially more far reaching than those associated with small reservoirs).
- Good geographical coverage so that a reasonable sampling of the broad range of British hydro-climatic conditions was made, such as sites from both upland and lowland regions. This also helped to ensure that climate change regional diversity was also reasonably sampled.
- Reservoirs forming component parts of complex reservoir systems were not targeted. Such sites were thought more likely to exhibit unique flood characteristics, raising questions as to how representative the findings from such sites could be.
- Reservoirs with other atypical or complicating features such as significant urban or artificial drainage areas were not considered.
- The targeting of regions with relatively high reservoir densities.
- The availability of the necessary dam information.

Based upon these criteria, fourteen dams from across England, Wales and Scotland were selected. Figure 3.1 indicates the regional location of these anonymous case examples, and Table 3.1 provides a summary of their pertinent design and physical characteristics.

| No. | Geographic location | Category | | Dam Type | Spillway | Upland\lowland | Reservoir Area* | SAAR** (mm) |
|---|---|---|---|---|---|---|---|---|
| 1 | Scotland (north) | A | PMF | Gravity/Earthfill | Uncontrolled | Upland | Large | 1500 - 2000 |
| 2 | Scotland (east) | A | PMF | Earthfill | Uncontrolled | Upland | Medium | 1000 - 1500 |
| 3 | Scotland (west) | A | PMF | Earthfill | Uncontrolled | Upland | Small | 1500 – 2000 |
| 4 | Scotland (west) | C | 1000 year | Earthfill | Uncontrolled | Upland | Small | 1500 – 2000 |
| 5 | N Eng | A | PMF | Earthfill | Uncontrolled | Upland | Large | 500 - 1000 |
| 6 | N Eng | A | PMF | Earthfill | Bellmouth | Lowland | Small | 1000 – 1500 |
| 7 | N Eng | A | PMF | Earthfill | Uncontrolled | Upland | Small | 1000 – 1500 |
| 8 | Wales (south) | A | PMF | Rockfill | Uncontrolled | Upland | Medium | 1500 - 2000 |
| 9 | Wales (north) | A | PMF | Earthfill | Uncontrolled | Upland | Small | >2000 |
| 10 | SW Eng | A | PMF | Rockfill | Bellmouth | Lowland | Medium | 1000 – 1500 |
| 11 | SW Eng | B | 10,000 year | Earthfill | Uncontrolled | Lowland | Small | 500 - 1000 |
| 12 | SE Eng | A | PMF | Rockfill | Bellmouth | Lowland | Large | 500 - 1000 |
| 13 | SE Eng | A | PMF | Earthfill | Uncontrolled | Lowland | Medium | 500 - 1000 |
| 14 | SE Eng | C | 1000 year | Earthfill | Uncontrolled | Lowland | Small | 500 - 1000 |

Reservoir area* Small < 1 $km^2$, 1 $km^2$ < Medium < 3 $km^2$, Large > 3 $km^2$

SAAR** – Standard Average Annual Rainfall

**Table 3.1 Characteristics of the selected dams and reservoirs**

It is recognised that the criteria of selecting a site based upon the generic form of the spillway (ie uncontrolled spillway) perhaps suggests a higher degree of homogeneity than actually exists. Flood release facilities of dams are usually site specific with seldom any two structures being identical. Several categories of spillway can be defined but there remain others which either do not fit conveniently into any category or possess features of more than one type of spillway category. In addition to the range in spillway shapes, the period of construction can have an important bearing on the capacity of dam spillways. For example, many older structures will be of masonry construction with arched bridges spanning the spillway channel. These bridges can have an important influence upon crest conditions through submergence effects. In contrast the more modern structures will either have bridges which do not intrude into the flow or will have bridges with only slender streamlined piers with minimal influence on flow.

### 3.3 Sensitivity analysis

Each of the fourteen example reservoirs was subject to flood sensitivity analyses in which the climatic factors used in the calculation of total surcharge were incrementally changed. The resulting sensitivity was then placed in the context of the present understanding of how climate change is likely to affect climatic storm conditions.

#### 3.3.1 Flood surcharge

The sensitivity analysis was based upon the standard procedure for estimating design total surcharge given in Floods and Reservoir Safety 3$^{rd}$ Ed (ICE, 1996). The procedure for estimating the flood surcharge component is largely based on the Unit Hydrograph\Losses rainfall-runoff model originally described in the Flood Studies Report (NERC, 1975).

The climate factors explicitly required in the flood surcharge modelling procedure are:

- design event rainfall depth
- design event rainfall profile
- standard average annual rainfall (SAAR)
- snow depth and snowmelt rate (where appropriate)
- catchment areal reduction factors

In the sensitivity analysis both the event rainfall depth and SAAR were incrementally changed. The resulting flood surcharge levels were observed to be about an order of magnitude more sensitive to changes in event rainfall depth than to equivalent percentage changes in SAAR. Increases in SAAR of 10% to 20% resulted barely in significant changes to predicted flood surcharge levels. The analysis was therefore simplified to use only changes in event rainfall depth coupled with a constant increase in SAAR equal to that of the UKCIP98 Medium-high 2050s scenario. Winter and summer events were modelled in all cases and the highest levels taken as the design level.

In the sensitivity analysis neither the design event rainfall profile[3] nor the snow conditions were altered since almost no guidance on how these two factors are likely to change in the future appears to be available.

The modelling used only the methods advocated in 'Floods and Reservoir Safety' for the derivation of input data and parameter values. The revised methods of estimating model parameters and input data suggested in the 'Flood Estimation Handbook' (Houghton-Carr, 1999) were not used. Appendix D describes what the possible implications of using the Flood Estimation Handbook procedures.

### 3.3.2 PMP rainfall in context of climate change

It is assumed that the probable maximum precipitation (PMP) rainfall depth can change with climate. The World Meteorological Organisation definition of PMP is:

"the theoretically greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year (with no allowance made for long-term climatic trends)" (WMO, 1986).

This definition alludes to the fact that current estimates of PMP assume a stationary climate. If this assumption is no longer observed (as is fundamentally implied in a climate change study) then the theoretical "upper bound" to rainfall may be changed and therefore PMP has been varied in the analysis.

[3] In this study it is recognised that compelling evidence exists (Collier and Hardaker, 1996) to suggest that the FSR symmetrical PMP design rainfall profile may not be particularly suitable for design storms with durations of between 10 and 24 hours. Collier and Hardaker suggest that asymmetric profiles related to Mesoscale Convective Systems (MCS) are probably more suitable, particularly in the north of the country. In a personal communication to the project team Collier suggested that the characteristics of particular very extreme storm profiles are in fact unlikely to change in the future but that the frequency with which particular storm profiles are likely to occur is likely to change.
No generalised or industry accepted methodology for the estimation of PMP across the UK using the present understanding of MCS characteristics has been developed. Although this might represent a valuable improvement to the estimation of PMFs it is outside the remit of this project.

### 3.3.3 Wave surcharge

The wave surcharge analysis advocated in the 3rd Edition of 'Floods and Reservoir Safety' was followed for each of the fourteen reservoirs.

The climate factors explicitly required in the wave surcharge modelling procedure which could more obviously be affected by climate change are:

- Mean annual maximum hourly wind speed.
- The direction adjustment factor (this relates to the direction of present prevailing extreme winds which in turn is related to storm tracks).

No climate change guidance on how prevailing wind directions may change is available. Therefore the sensitivity analysis was performed by simply changing incrementally the existing site specific design wind speeds.

### 3.3.4 Total surcharge

Total surcharge is calculated by adding the predicted flood and wave surcharges together. From the sensitivity analyses a matrix of total surcharge was obtained that provided the predicted total surcharge for any combination of changes to event rainfall depth and wind speed. The possible changes to total surcharge resulting from projected future changes in event rainfall depth and extreme wind speeds can then be assessed. At present these projected changes to storm climate are somewhat speculative. However, the sensitivity matrices may well remain valuable for the interpretation of future improved climate change projections.

### 3.3.5 Summary of methodology

The approach followed was to assess the surcharge sensitivity of example reservoirs to incremental changes in the climatic factors affecting the design estimation of total surcharge. Fourteen example reservoirs were selected such that their design, hydro-climatic and geographical characteristics were reasonably representative of the characteristics of the overall population of British dams. The surcharge estimation procedure outlined in the third edition of the Floods and Reservoir Safety guide was followed. The key climatic attributes incrementally changed were: i) storm rainfall depth (in the estimation of flood surcharge), and ii) wind speed (in the estimation of wave surcharge). Other related climatic factors, such as storm profile, snowmelt and wind direction, were considered but until more is known about the likely effect of climate change on these it was considered premature to adjust them. The implications of the resulting site sensitivities could then be framed in terms of the currently available climate change projections.

# 4. Climate Change

## 4.1 Introduction

This section deals with the issues of climate change scenario construction and the nature of the scenarios used for this study. The first part is a brief description of the various methods available for developing climate scenarios, focusing particularly on the issues of downscaling (creating scenarios at finer time and space scales than currently available from Global Climate Models). The second part then describes the scenarios used for this study of reservoir safety, developed from the UKCIP98 CD-ROM.

## 4.2 Climate change scenarios: uncertainty and construction

With a growing body of evidence suggesting a human-induced influence on global climate, it is necessary to be able to assess the vulnerability of systems to any consequent changes in climate. This is one of the primary reasons for construction of climate change scenarios. Such scenarios present coherent, systematic and internally-consistent descriptions of a future climate (Hulme and Jenkins, 1998). While it is not always the case, most climate change scenarios are constructed from the output of GCMs and are used for sensitivity/vulnerability analyses, impact or adaptation studies.

It is not yet possible to speak in terms of climate change predictions (or forecasts), largely due to the still significant discrepancy between the climate sensitivities[4] of GCMs. There are other uncertainties associated with climate scenarios:

- the future rates of emission of gases and aerosols responsible for global warming are unknown;
- the regional patterns within GCMs can be significantly different reflecting both the way that physical processes are represented and the scale to which they are modelled
- it is difficult to distinguish between natural climate variability and climate changes induced by human activity
- incomplete understanding of various feedback processes (for example carbon cycle, cloud, atmosphere and ocean feedbacks);
- the potential for rapid non-linear change (for example a change in the thermohaline circulation of the world's oceans or the break up of the West Antarctic Ice Sheet)

[4] For each GCM there is a different response, in terms of the global mean temperature, following a doubling of carbon dioxide concentrations – this is termed the climate sensitivity.

There are very many requirements of climate change scenarios depending on the precise nature of the analysis to be carried out. For some decisions only quite qualitative scenarios are required whereas for others highly quantitative and complex scenarios are needed, even with associated probabilities. As well as the nature of the scenarios, the resolution of scenarios varies. For some applications GCM-scale (3.75° longitude by 2.5° latitude for the Had CM2 model of the Hadley Centre GCM, as shown in Figure 4.1 over the UK) are sufficient, but for many, particularly hydrological studies, a finer, catchment-scale resolution is needed. Equally, some modelling studies require sub-daily or daily data, whereas others can cope with the monthly changes in climate variables from GCMs. The following sections outline some of the methods available for constructing scenarios other than those directly available at the GCM-scale on a monthly time-step. Broadly, these downscaling methods can be split in four categories (Wilby and Wigley, 1997), although usually no method falls exclusively into just one of these groups. The fifth group described in this section considers some, fairly limited approaches that do not directly use GCM output:

(i) Regression and simple statistical methods

These methods were among the first used to provide sub-grid information. Generally this technique involves developing relationships between finer-scale (site) parameters and the coarser-scale (GCM) predictor variables. These relationships can then be used in predictive mode using finer resolution output from regional climate models to provide the spatial detail. A simpler approach to producing climate change scenarios at a finer spatial resolution than the GCM output affords is to use simple interpolation techniques. These techniques use the single GCM values attributed to the centre of each cell, as the basis for interpolating a finer mesh of data - no "new" spatial information is provided through this simple interpolation. The UKCIP 98 scenarios are constructed following that technique to produce grids at a 10-km resolution (Hulme and Jenkins, 1998).

(ii) Weather-typing

Typically these methods involve developing relationships to statistically relate station or local area meteorological information to a given weather classification scheme, such as Lamb's Weather Types for the British Isles (Lamb, 1972). The benefit of this particular method of downscaling is that it is based on sensible, physical relationships between large-scale climate and more local-scale weather. Indeed, the dependence of daily (Wilby et al., 1998; Galambosi et al., 1996) and sub-daily (Svensson et al., 2000) rainfall on indices of large-scale atmospheric circulation has been demonstrated. However, it is not certain that relationships between climate and weather (and in particular rainfall) will remain similar under a different climate

(iii) Stochastic weather generators

At the heart of most weather generators are first, or multiple-order Markov chain processes. These model the probability of precipitation (and sometimes the depth also) on a given day, based on the information about the previous day(s). Many climate change impact studies have used such models (Faulkner et al., 1997; Mearns, et al., 1999; Wilks, 1999) to provide sub-monthly scenarios of rainfall in particular. The problem with their application, however, is associated with a lack of knowledge of how to adjust the model parameters in a physically realistic and internally consistent way to simulate a future climate (Wilby and Wigley, 1997).

(iv) Regional climate models

This technique for downscaling the output of GCMs involves the use of finer resolution limited area models, perhaps resolving on to 20-50 km grids. These regional models are embedded within a limited geographical area of the GCM, with the GCM being used to set the time-dependent boundary conditions. Despite some obvious advantages of spatial and temporal scale gained using regional climate models, they remain computationally demanding and expensive. Additionally, they are entirely dependent on the quality of the grid-point GCM data used to drive the models (a deficiency that also applies to the weather-typing approaches).

(v) Analogue scenarios

An alternative way of understanding the behaviour of extreme events during abnormally warm periods is to try analogue approaches. These techniques are not particularly sophisticated and do present a host of problems, which in most cases (this study included) preclude their use. There follows a brief description of the techniques and the reasons the methods have not been used in this analysis.

(a) Temporal analogues – This technique involves the investigation of the time series at the study location for two periods in the record when the average temperatures were significantly different. If such periods are found then the characteristics of the extreme rainfall or wind speed may be compared to gain an understanding of how these variables behave during periods of relative warmth or cold. The main issue with this approach is usually the length of record, especially when studying extremes. Time series of extreme rainfall or wind speed will be rarely long enough to allow two significantly long (30 years would be ideal) periods with different average temperatures to be located. This is the case for the current study and meant the temporal analogue method of scenario construction could not be used.

(b) Spatial analogues – The method has greater potential for application, but it is the view of the research team that it presents too many problems and uncertainties to allow its use. Rather than searching the site records for two periods with different temperatures, an alternative, "similar" site is chosen that experiences a climate with a higher average temperature. This means that the issues of record length are not so great compared to the temporal analogue, but the geographical differences between the sites create an array of new problems. No matter which site is chosen there will always be fundamental differences in the way extreme events are generated over the two areas. This means that the climate and associated weather of the "warm site" will never be re-created at the "cold site" in a future warmer world. These issues are discussed in more detail, and an example shown in Reynard et al (1998).

### 4.3 Climate change scenarios for this project

The objectives of this project make the application of standard climate change scenarios particularly difficult. An investigation of the implications of climate change for reservoir safety in Britain necessarily requires scenarios of changes in the frequency and magnitude of the most extreme weather events. This type of climate scenario information is not routinely available from the traditional sources such as the output of Global Climate Models (GCMs).

Given the particular problems posed by the study and the current state-of-the-art of climate change scenario construction techniques, this project took a slightly different approach. A sensitivity analysis was carried out for each of the study catchments whereby the rainfall and wind speed values were systematically changed to assess the sensitivity of the water levels of each reservoir to changes in climate. These changes in climate were then framed in terms of the information that was available for changes in rainfall and wind speed in the UK from the UKCIP98 scenarios. In this way it was possible to see which of the matrix of changes in water level might (tentatively) be considered more, or less, likely.

The core set of climate change scenarios used were those from the UKCIP98 CD-ROM produced for the UK Climate Impacts Programme (UKCIP) by the Climatic Research Unit, University of East Anglia (Hulme and Jenkins, 1998). The Technical report for these scenarios was published in October 1998. All the UKCIP98 scenarios (essentially four) were derived from the output of the GCM developed at the Hadley Centre for Climate Prediction. The range of these four scenarios reflects the uncertainties in modelling the global climate in the next century. The various assumptions behind the four UKCIP98 scenarios are briefly described in Table 4.1.

| Scenario | Greenhouse gas emission scenario | Climate sensitivity | Global mean temperature change (ΔT°C) | | |
|---|---|---|---|---|---|
| | | | 2020 | 2050s | 2080s |
| Low | IS92d | 1.5°C | 0.57 | 0.89 | 1.13 |
| Medium-low | GGd (0.5%pa) | 2.5°C | 0.98 | 1.52 | 1.94 |
| Medium-high | Gga (1%pa) | 2.5°C | 1.24 | 2.11 | 3.11 |
| High | IS92a | 4.5°C | 1.38 | 2.44 | 3.47 |

**Table 4.1 Summary of assumptions behind the four UKCIP98 scenarios**

The IS92a and IS92d emission scenarios are those described by the Intergovernmental Panel on Climate Change (IPCC, 1996). The GGa and GGd notation relates to two levels of greenhouse gas emissions used in the HadCM2 experiments. The GGa forcing is an increase of 1% per annum in the $CO_2$ equivalent[5] concentrations from 1990 to 2100. The GGd forcing is equivalent to a 0.5% per annum increase.

The sensitivity analyses carried out in this project was concerned with three issues relating to these climate scenarios: changes in extreme rainfall, changes in maximum annual wind speed and joint changes in both rainfall and wind speed. The following sections describe the type of information that is available from the UKCIP98 scenarios for each of these.

[5] $CO_2$ equivalent refers to the fact that HadCM2 does not handle the various GHGs individually. It uses a $CO_2$ concentration that is equivalent to the sum of all GHGs. The HadCM3 model can handle the individual GHGs.

(i) Rainfall

The changes in rainfall that are described are all in percentage terms. These represent changes from a 30-year baseline period - 1961-1990. Figure 4.2a shows the annual average rainfall (in mm) on a 10km grid over Britain for this baseline period.

The changes to this baseline by the 2050s (under the medium-high scenario) are shown in Figure 4.2b. Annually, rainfall increases across the UK with the greatest changes (more than 10%) in eastern Scotland, Northern Ireland and the Midlands. The smallest increases are in the south and parts of Wales. However, these average annual changes mask the more complex pattern of monthly changes. Figure 4.3a-d show the changes in average monthly precipitation for January, April, July and October (used to represent the seasons), again for the 2050s (medium-high scenario). The temperature scenarios suggest a warming throughout the year, although the increases in temperature are slightly higher in the winter than the summer. This means that the coupling of the rainfall and temperature scenarios suggests milder, wetter winters and warmer, drier summers.

The scenarios presented in Figures 4.2 and 4.3 only describe changes in the long-term average rainfall. There is less information available concerning changes in extreme rainfall. The UKCIP98 technical report (Hulme and Jenkins, 1998) suggests that average precipitation intensities increase in both summer and winter for northern parts of the UK, with the most intense events several times more frequent than at present. For the south, rainfall intensities and their frequency increase only in the winter. In the summer, because of the decrease in average rainfall, there will be fewer intense events, although the proportion of the summer rain that falls during storm events may increase. However, only qualitative information is available. Quantitative scenarios relative to changes in extremes are not yet adequately modelled by GCM.

It is important to assess the climate change scenarios in the context of current and future climate variability. The current range of natural variability, particularly for rainfall, means that it is often difficult to detect the signal due to climate change from the noise due to the variability.

This is especially true when looking at climate impacts for time-horizons close to the present, even when ensemble[6] prediction techniques are used. It is also possible that the impact due to a change in average climate, either for the climate variable (e.g. rainfall) or the impact indicator (e.g. water level in the reservoir) does not produce a trend in the time series that shifts the record beyond the range of current natural variability.

The scenarios provided by the GCMs are not yet accurate enough to give information on changes in the storm profile and in the design duration, mainly because of the difficulty to model rainfall at fine time scale. However, changes in design depth are reflected by the changes in average precipitation intensities and considered representative of the changes in the design rainfall.

(ii) Wind speed

Some wind speed data are available from the UKCIP98 CD but the mean maximum daily wind speeds are only available for the baseline period. This means that for this study the average wind speed changes were used, as with the precipitation changes. The average daily wind speed, in $ms^{-1}$, for the 1961-1990 period is shown in Figure 4.4a, with the annually averaged percentage change shown in Figure 4.4b.

The wind speed changes are smaller, in percentage terms, than the rainfall changes, ranging from small decreases (1%) in the south, to slight increases (1%) in the north. Like rainfall, these annual average changes mask a seasonal pattern. Figures 4.5 a)-d) show the monthly changes in wind speed for January, April, July and October. The autumn and winter tend to become windier, while the spring and summer become less so.

Changes in the average wind speed only provide very limited information for a study such as this. There is only very limited quantitative information about changes in extreme daily wind speeds. The frequency of winter and summer gales is likely to change, depending on the severity of the gale and the time period selected. Table 4.2 contains these data for the UK from the UKCIP98 report. The high degree of variability in the changes illustrates the difficulty in developing scenarios for changes in the frequency and magnitude of extreme events and the problems of detecting a climate change signal in a series with a

[6] Ensembles: The model predictions of climate change could depend upon the choice of point on the control run at which the increasing greenhouse gas concentrations are introduced. For this reason in the UKCIP98 scenarios four identical model experiments, with the same historical changes and future changes in greenhouse gases, are initiated from four different points on the control run, this is known as an ensemble of predictions.

great deal of inherent natural variability.

| | | Present (gales/year) | 2020s (% change) | 2050s (% change) | 2080s (% change) |
|---|---|---|---|---|---|
| Winter | Gales | 10.9 | -1 | -9 | -5 |
| | Severe gales | 8.5 | -1 | -10 | -5 |
| | Very severe gales | 1.4 | +8 | -10 | +11 |
| Summer | Gales | 1.8 | +3 | 0 | +14 |
| | Severe gales | 1.1 | 0 | +2 | +15 |
| | Very severe gales | 0.1 | +25 | -16 | +9 |

**Table 4.2. Changes in the frequency of summer and winter gales under the medium-high scenario (The present number of gales was determined from the GCM output for the 1961-1990 period, not from the historical record).**

For any of the reservoirs in this study there are likely to be local factors that further enhance, or even dampen the effect of these scenarios. Local topography might serve to channel the wind in certain way, so as to exaggerate the changes in the gales frequencies listed above. Equally, a change in the wind regime of the catchment might involve a change in the average orientation of storms, which could have either a beneficial, or a detrimental effect on the vulnerability of the reservoir to extreme events.

(iii) Joint changes in rainfall and windspeed

This section describes how rainfall and wind speed might change jointly. This leads on to how the climate change envelopes have been derived to provide a guide for sensitivity analyses.

Figure 4.6 plots the change in average rainfall against the change in average wind speed for all available scenarios for one of the reservoirs for the 2050s[7]. These include the data for each month, season and relative to the whole year for the low, medium-low, medium-high and high sensitivity scenarios from UKCIP98. The rectangle that is described by the points defines the climate change envelop..

The reservoir sensitivity analysis requires information on winter (as defined in the FSR as the 6-month period November to April) and summer (6-month

[7] Only the time horizon 2050s is studied here. Time horizons closer to present (e.g. the 2020s) are usually considered with caution because of the difficulty to detect the climate change signal from the natural climate variability. Time horizons further away (e.g. the 2080s) may be less certain if the international community conforms to agreements such as those decided in Kyoto to reduce gas emissions.

period May to October) changes. Similar rectangles of seasonal climate change can be drawn and are used to define the seasonal climatic change envelopes (see Appendix E). The use of all four scenarios from the range of sensitivities (low to high) means that the most extreme average monthly changes are always included. This climate scenario surface is not intended to define the sensitivity analyses, rather it should be used to frame the findings of the analyses within the range of changes described by the UKCIP98.

It must be stressed that none of the scenarios have been defined in terms of either the change in maximum daily rainfall or maximum wind speed. These data are not currently available. Instead, the scenarios have been developed from the available data on changes in the average rainfall and wind speed. It is recognised that this is a compromise, but an unavoidable one.

As described in section 4.2, several methods of downscaling climate change scenarios from GCMs to finer time and spatial scales are currently used in the scientific community, some of them having a high degree of complexity. The use of the UKCIP98 scenarios, including simple downscaling procedures, was one of the requirements of the study, and no additional downscaling was considered here. This is a deliberately simple approach, which has the advantage not to add any further uncertainty to those inherent to GCMs as opposed to more complex downscaling techniques.

A summary, including similar figures to that of Figure 4.6, for each of the 14 sites is attached at Appendix E.

The use of the entire rectangle described by the UKCIP98 scenarios (the area defined by the dashed box in Figure 4.6) to describe the climate change envelope, rather than just a few of the extreme points, is an attempt to include a factor for some of the additional uncertainties. For example, as already discussed, the scenarios do not describe changes in the extremes themselves and the project has not allowed for the development of scenarios that include changes to the design storm profile as well as the depth.

The rectangle described in Figure 4.6 encloses all the UKCIP98 points, but also allows for some more extreme scenarios. For example, the most extreme positive changes, as defined by the UKCIP98 CD-ROM are:

(a) 9.2% increase in rainfall, coupled with a 0.9% increase in wind speed – UKCIP98 High scenario.

(b) a 4.6% increase in rainfall, but a 1.9% increase in wind speed - UKCIP89 Medium-high scenario.

(c) The use of the box allows for a more extreme scenario to be defined; a 9.2 % increase in rainfall coupled with a 1.9% increase in wind speed.

(iv) Additional uncertainties

A warmer world will obviously have impact on snow accumulation and melt rates. It is unclear, however, exactly which way these changes will go and how they will interact. One might expect the influence of snowmelt events to decrease in a warmer climate, but with increased winter precipitation the far north and higher altitudes might actually experience more snowfall, at least for the early part of the 21st Century. However with higher average temperatures it is likely that snow will not lie for as long as at present, reducing the potential for snow pack development. Future warmer conditions may also be more conducive to rapid melts Any scenarios of snow fall and consequent snow melt are still difficult to construct and therefore the impact of a change in the snow regime on extreme events as they affect reservoir safety, must remain one of the uncertainties.

### 4.4 Summary

This report makes use of scenarios specially designed by the UK Climate Impact Programme (UKCIP98) for impact studies in the UK. A core set of scenarios representing predictions under four different emission scenarios is used, reflecting the uncertainty inherent to GCM outputs.

Assessing the impact of climate change on the safety of British reservoirs requires knowing how rainfall and wind speed may change in the future. Information on changes in the magnitude and frequency of the most extreme events, the design storm profiles, gale events or on snow melt are not available from GCM at present. Thus, the study focuses on changes in average daily intensity rainfall and in mean daily wind speed. Changes to the baseline (1961-1990) by the 2050s indicate increase in annual rainfall across the UK, with the greatest changes (more than 10 %) in eastern Scotland, Northern Ireland and the Midlands. Monthly changes in both rainfall and temperature suggest milder, wetter winters and warmer, drier summers. Wind speed changes are smaller, in percentage terms, than the rainfall changes, ranging from small decreases (1 %) in the south to slight increases (1 %) in the north, with the autumn and winter becoming windier, while the spring and summer become less so. When considered together, those changes define a "climate change surface" providing a guide for the sensitivity analysis, and also allow for some more extreme scenarios to be considered, such as joint occurrence of the most extreme changes in both rainfall and wind speed.

## 5. Presentation of Sensitivity Results

### 5.1 Sensitivity analysis

The sensitivity analysis based solely upon changes to design rainfall depths does not, in itself, tie the analysis to any particular time horizon. However, in an attempt to account for the influence of changes in general wetness, the 2050s Medium-high projected average annual rainfall was used in the model (Table 5.1). The analysis can therefore be considered to be most appropriate for the 2050s time horizon, although of relevance to other time horizons since the predictions are relatively insensitive to the potential changes in average annual rainfall.

| Reservoir site reference no. | Location | Medium-high projected* % change in average annual rainfall by the 2050s |
|---|---|---|
| 1 | Scotland | 4 |
| 2 | Scotland | 6 |
| 3 | Scotland | 4 |
| 4 | Scotland | 5 |
| 5 | N. England | 3 |
| 6 | N. England | 2 |
| 7 | N. England | 2 |
| 8 | Wales | 2 |
| 9 | Wales | 1 |
| 10 | SW England | 2 |
| 11 | SW England | 2 |
| 12 | SE England | 0 |
| 13 | SE England | 1 |
| 14 | SE England | 1 |

* Based upon the 10 km grid data provided on the UKCIP 98 CD-ROM

**Table 5.1 Projected change in average annual rainfall by the 2050s for each of the 14 example sites. (Based on the Medium-high scenario)**

The results of the sensitivity analysis, in which both event rainfall depth and wind speed were incrementally changed, are given graphically in full in Appendix F. Each reservoir has two graphs associated with it – one for the winter design conditions and one for the summer conditions. These graphs allow the limits of the climate change scenario to be compared with the equivalent %age increase in total surcharge. This is specific to a reservoir of the size and type represented in that chart for the broad climatic region of the

UK to which it is assigned. The X and Y axes mark the percentage changes in storm rainfall depth and wind speed used in the sensitivity analysis. The numerical spot values are the estimated total surcharge levels for each combination of rainfall and wind speed change on a 5% grid. The origin therefore represents the predicted surcharge level without any imposed change to the design values of either the storm rainfall or wind speed[8]. The diagonal lines represent constant levels of percentage increase in total surcharge level. These have been drawn on in accordance with the background spot levels of predicted total surcharge. The shaded rectangle represents the seasonal climate change surface (as defined in Chapter 4).

In all 14 example cases the wave surcharge did not exceed 50 percent of the total surcharge therefore in accordance with FRS it was not necessary to consider a calculated wave surcharge resulting from a < 200 year wind speed in any of the cases.

Table 5.2 summarises the largest projected changes to seasonal total surcharge implied by the climate change envelopes for the 2050s medium-high scenario for the fourteen reservoirs studied.

| Reservoir site reference no. | Location | Maximum % change in total surcharge | |
|---|---|---|---|
| | | Winter | Summer |
| 1 | Scotland | 7 | 8 |
| 2 | Scotland | 11 | 10 |
| 3 | Scotland | 9 | 7 |
| 4 | Scotland | 7 | 7 |
| 5 | N. England | 9 | 8 |
| 6 | N. England | 9 | 7 |
| 7 | N. England | 8 | 6 |
| 8 | Wales | 7 | 5 |
| 9 | Wales | 4 | 3 |
| 10 | SW England | 7 | 4 |
| 11 | SW England | 7 | 5 |
| 12 | SE England | 9 | 6 |
| 13 | SE England | 9 | 8 |
| 14 | SE England | 8 | 8 |

**Table 5.2 Maximum projected percentage change in total surcharge**

[8] Within the calculations the 2050s projected increase in SAAR has been used. This tends to marginally change the predicted total surcharge level from the value calculated for the present day situation. Therefore although the origin value is not strictly the present day design surcharge level, it will be relatively close to it.

As can be seen the maxima indicated rarely exceed 9% and on average are 6.5% summer and 7.9% winter. The envelopes shown on the sensitivity charts in Appendix F however give a better impression of the overall impact of the range of climate change scenarios for each site.

## 5.2 Discussion

The FSR rainfall-runoff model was designed and calibrated to simulate present day[9] design conditions. The model was not developed with the intent to be able to accommodate a changing climate. Its use on climatic data that is increasingly removed from the data set to which it was calibrated will progressively increase the uncertainties of the output. However if the changes are relatively small and within the range of the calibration dataset the model will probably reasonably capture the likely response of the system. The 5% to 15% changes in wind and rainfall that seem to be of most relevance in this study, are thought to fall within this category.

The suitability of using the projected changes in average annual rainfall within the seasonal assessments is perhaps more questionable since the climate change projections suggest marked differences in seasonal rainfalls. However the model suggests that the systems are an order of magnitude less sensitive to these indices of wetness than to equivalent changes in storm rainfall depth. The solution of only using the projected Medium-high change in SAAR was possibly not ideal, but given the predicted relative sensitivities and the large uncertainties inherent in the climate change projections, this was not judged to be inappropriate.

For the purpose of trying to ascertain whether the impact of climate change could pose a significant risk to reservoirs the potential consequences of the worse case combinations of storm rainfall depth and wind speed are highlighted in Table 5.2. This in some respects is somewhat misleading but does, within the bounds of the methodology followed, provide a provisional upper level. Too much reliance upon the detail of the seasonal climate change envelopes should not be inferred. Rather they should be viewed as providing an indicative idea of the conceivable magnitudes of change, based upon the incomplete level of information currently available. As highlighted in Chapter 4 the scenarios of climate change currently available do not indicate how short-duration rainfall extremes might be modified in a changed climate. Until a better understanding is established the changes in average monthly intensity are used as a surrogate, albeit a somewhat imperfect one.

[9] The original FSR model was developed during the 1970s and elements of the model have subsequently been reviewed. Present day is therefore used here to broadly represent the second half of the twentieth century.

Although the climate change envelopes are provisional and need improving, the underlining sensitivities of the reservoir systems to changes in storm rainfall depths and wind speeds are likely to remain useful for future assessments. However, if the characteristics of storm profiles are believed to be significantly changed in the future (or indeed if the present profiles are superseded by significantly different ones (Collier & Hardaker,1996), a review of the sensitivity analysis would be required. At the moment, it would appear possible only to make a simple allowance for potential climate change by adjusting design rainfall depths. In safety evaluations overseen by the Nuclear Installations Inspectorate, some assessments look at the sensitivity of the final answer (e.g. the water level adjacent to a critical installation) to a nominal (e.g. 10%) change in the design rainfall depth. Until more is known about the likely effect of climate change on spatial and temporal profiles of extreme rainfall events, it appears premature to adjust the standard temporal profiles and area reduction factors used in reservoir flood estimations.

### 5.3 Summary

In the absence of guidance on how storm event characteristics are likely to be affected by climate change the projected changes in average monthly intensities are used as provisional surrogates. For the purpose of trying to ascertain whether the impact of climate change could pose a significant risk to reservoirs the potential consequences of the worst case combinations of storm rainfall depth and wind speed are highlighted for the 2050s time horizon. For the fourteen reservoirs studied these worse case combinations suggest that winter event rainfall may increase within the range 7 - 23% and winter wind may increase by 1 – 4%. Similarly summer rainfall may increase by 5 – 16% and summer wind speeds by 2-5%. In the context of the total surcharge sensitivity analysis, the worse case changes in winter surcharge are suggested to be in the range of 4 – 11%, and summer values in a similar range of 3 – 10%. No obvious regional pattern in terms of changes in total surcharge are observed.

Too much reliance upon the detail of the seasonal climate change envelopes, which describe the range of potential changes, should not be inferred. The envelopes should only be viewed as providing, at best, an indicative idea of the conceivable magnitudes of change that may occur. The projected worse case changes in surcharge must therefore be treated as provisional.

The key issue is whether reservoir safety would be seriously compromised by surcharge sensitivities such as those indicated here. Certainly the impacts are not great in percentage terms particularly when viewed against the uncertainty involved in the selection of input parameters for flood work in general. The associated conservatism of approach in matters of surcharge calculation and freeboard allowance also suggests that the sensitivity of the scale indicated is not great. However, only inspecting engineers for specific reservoirs should interpret these findings against the prevailing circumstances.

## 6. The Impact of Increased Flood Rise and Wave Run-up on UK Stock of Reservoirs

### 6.1 Preamble

Having determined the theoretical response of the selection of representative reservoirs to incremental changes in rainfall and winds in terms of increased total surcharge, and related that to climate change scenarios, it is necessary to discuss the impact that this may have on the general stock of UK dams. Most reservoirs show approximately a +5% sensitivity to the worst case prediction of storm depth and windspeed changes for the 2050 time horizon.

### 6.2 Total Surcharge Results from Representative Reservoirs

Total surcharge was found to be in the range 1 metre to 4 metres from 12 of the representative reservoirs selected with two extremely large reservoirs giving total surcharge of over 5 metres. A five percent change in total surcharge represents an increase of between 0.05 metre and 0.27 metre in the combined wave and flood surcharge for the representative dams.

### 6.3 UK Stock of Reservoirs

#### 6.3.1 Dams

There are approximately 5000 dams of varying size in the UK with around 2600 of these whose reservoirs are of sufficient storage capacity to fall under the legislation of the Reservoirs Act 1975 which covers all reservoirs which hold more than 25,000$m^3$.

The majority of the dams in the UK are embankment structures with some 2000 coming within the ambit of the Act and they fulfil the purpose mainly of providing stable water supplies but also hydro-electric power and more recently recreational facilities for a modern social environment. Of these 2000 dams, some 1500 are over fifty years old and of these more than 1000 are centenarians. Those falling within the ambit of the Reservoirs Act 1975 are all inspected at least every ten years and are under the regular supervision of a qualified engineer between inspections. These arrangements are recognised to be effective in maintaining dam safety.

Large dams comprise about 570 number out of the 2000 embankment stock. Large dams are defined as dams which retain water to a height greater than fifteen metres above the lowest point of the foundations of the structure or above the average level of the surrounding land or ten metres if noteworthy in some other way (ICOLD, 1983).

The distribution of dam numbers whose reservoirs are of sufficient capacity to be under the Act are summarised in Table 6.1.

| Embankment Dams and Reservoirs under the Act | | | |
|---|---|---|---|
| Total Number | Dams over 50 years | Dams over 100 years | Large Dams |
| 2000 approx. | Some 1500 | > 1000 | About 570 |

**Table 6.1 - Embankment Dams**

### 6.4 Embankment Dams and Flood and Reservoir Safety

External erosion has been recorded as the main cause of embankment dam incidents in only 24 percent of the total incidents where earth embankments are concerned (Charles and Boden, 1985). Whereas over 50 percent of the earth embankment incidents recorded (Charles and Boden, 1985) in the UK have involved some form of internal erosion. External erosion refers to events where the dam crest has been overtopped as a result of floods of extreme return period plus waves running up the upstream face of the dam, and the resulting overtopping discharge eroding the downstream slope of the structure.

In terms of the knowledge of dam performance, UK reservoirs can be defined as falling within the following boundaries:

(a) Large reservoirs with normally large dam structures mainly under the control of major organisations and probably well-maintained to current standards

(b) Small reservoirs with normally small dam structures in private ownership and possibly marginally maintained to current standards.

Many dams of all types are marginal in terms of freeboard. Sometimes this is a function of limited spillway capacity and sometimes the effects of settlement on the crest.

Spillways – the type and configuration of spillway has a major impact on flood rise but is also sensitive to the selection of hydraulic discharge parameters in the calculation of this value.

Crest details – all conventional embankment crests are sensitive to increased surcharge unless they currently have a greater than required freeboard for the appropriate standard (probably for reasons other than surcharge provision) in this respect. Parapets and wavewalls can, in some circumstances, provide greater tolerance to percentage increases in surcharge.

## 6.5 Dam Crest Features

Within the broad group of embankment dams crest features have an influence on dam freeboard. The three most common examples of crest treatments are dams with wave walls, those with parapet walls and those with conventional crests. Wave walls normally comprise solid retaining structures and the main design parameters could include wave forces, run-up levels, overtopping discharges and reflection performance. Parapet walls on the other hand are used to protect vehicular and pedestrian traffic on the dam, or to compensate for long-term settlement. They are not normally designed against wave forces and run-up. A conventional crest design is where there is no wall and the top of the embankment relates to maximum freeboard level

From experience of estimating flood rise and wave surcharge in reservoir flood studies, for large dams, flood rise and wave surcharge would both typically exceed 1 metre giving a total surcharge on average in excess of 2m. Small dams offer typical values of 0.5m flood rise, with a similar order of magnitude for wave surcharge, making the total surcharge just over 1m. These generalisations compare closely with the actual findings from 12 of the 14 representative reservoirs.

## 6.6 Weightings and Classifications of Embankment Dams Sensitivity with Respect to 5 percent Changes to Combined Surcharge.

Having examined the sensitivity of the sample of representative reservoirs, some work was carried out to check for any commonality of trends that could be attributed to one or more of the general characteristics of a reservoir.

A matrix was created consisting of eight groups with two differentiating between large dams and small dams and a further sub- group of three considering the crest features. Sensitivity weightings based on type of crest and susceptibility to overtopping external erosion were attached to each group and sub-group to determine a total weighting. This proved to be subjective and inconclusive and accordingly it is not believed to be realistic to form firm opinions on the basis of the limited sample size used in this study.

### 6.7 Number of Dams

Large dams comprise about 28% of all embankment dams within the ambit of the Reservoirs Act, and of these only about 10% will have a conventional crest. Thus in terms of numbers the dams most sensitive to a 5% increase in total surcharge (i.e. large dams with conventional crests) number probably less than 50.

### 6.8 Hazard Control

#### 6.8.1 Dam Categories

The four recommended classes of dams and reservoirs and their associated design standards are listed in Table 1 of FRS.

The UK approach to high hazard dam safety is based on the concept of the elimination of the possibility of failure of a dam resulting from flood (and wave) surcharge where there is a risk to life. Dam engineering is therefore virtually unique in the areas of engineered structures which aims (for Category A dams) at the total elimination of specific flood risk. The other dam categories however will have a more definite probability of failure.

#### 6.8.2 Reservoirs Act 1975

The Reservoirs Act 1975 provides for monitoring of every reservoir by Supervising Panel engineers. In their inspection reports, Inspecting engineers are required to bring to the attention of the Supervising Engineer any aspects which should be watched over the period prior to next inspection. One such area could be in reviewing any evidence of climate change at the site, which might affect the safety of the structure. No change would be required to legislation to allow this to be done, but it could be highlighted as an issue in, say, the 2nd edition of the Guide to the Reservoirs Act, when published.

## 6.9 State of the Art

### 6.9.1 Safety Design Standards

No standards are published for the UK but the 3rd edition of the Floods and Reservoir Safety (FRS) guidance document is used as the de facto standard for assessing freeboard, although Inspecting Engineers have discretion over the precise application of the guidance.

### 6.9.2 Research Programmes and Innovation

The impact of research and innovations within the reservoir industry may have a wide ranging effect on the results of any climate change predictions over the next 50 years or so. Risk situations may be introduced which have little historical precedence but on the other hand there may be less onerous conditions recommended through other published guidance. Some of these points are illustrated below as a means of demonstrating that climate change is only one aspect that needs to be considered in future reservoir safety programmes:

- Snowmelt - Although the UK has few experiences of purely snowmelt floods , melting snow has often combined with heavy rainfall to produce flooding, such as in the south of England in 1947. The FSR 100 year melt rate of 42mm/day has provoked much debate. A physically derived maximum snowmelt was not defined, but 42mm/day was felt to be suitable for design purposes. The map (Fig.2) in FRS guide indicates hatched areas where higher rates of snowmelt may be expected but future research may quantify higher (or lower) snowmelt rates and increase (or decrease) significantly the snowmelt contribution to large winter floods in the UK.

- The publication of FEH may have severe implications on spillway design standards as extreme event rainfalls estimated using FEH may exceed the current FSR estimates by a considerable margin.

- Other research programmes as listed in Appendix 2 of the FRS guide will yield further results of relevance to the estimation of design floods.

- The working party on FRS (1978) recommended that after ten years experience had been gained by panel engineers in using the guide, its contents should be reviewed and, if deemed necessary, it should be revised. No such preface is included in the current Third Edition. However, DEFRA are now looking at the concept of an integrated reservoir safety approach which will consider risk and frequency of occurrence for all factors affecting dam safety e.g. floods, internal erosion, stability, seismic safety etc.

## 6.10 Spillway Capacity and Associated Structures

A finding that a spillway will not (safely) pass the flood indicated in the recommended standards does not necessarily mean that the dam should be classified as unsafe.

The capacity of a spillway is a function of not only the spillway size, shape, dimensions etc. but also can be influenced by downstream conditions. This is particularly true of embankment dams. The degree of inadequacy of the spillway to pass the appropriate flood and the probable adverse impacts (of dam failure) resulting from overtopping must be considered as an issue

However, in addition to the spillway, water may be released from a reservoir through a range of outflow facilities. Regulation of the water level by operational measures (eg an operating requirement to reserve 10% of capacity for the winter periods) may bring modest benefit to the risk management regime and in certain circumstances will be one option to be considered to minimise costs in additional overflow works provision.

## 6.11 Overtopping

Wave overtopping can cause structural damage to embankments resulting in hazardous conditions on top of the dam. The crest height should ensure that wave overtopping of the dam is kept to acceptable levels. Guidelines for safe overtopping discharges are given in the CIRIA/CUR Rock Manual (1991). Figure 10.1 in the Manual gives safe thresholds of overtopping based on different access requirements and uses. Overtopping discharge occurs as a result of waves running up the upstream face of a dam.

If wave run-up levels are high enough water can reach and pass over the crest and this defines the green water overtopping case. This study has assumed an infinite freeboard condition for the selected (synthetic) dams. There are some cases where an assessment of the effective contribution of a wave wall to freeboard may curtail the wave surcharge. A second form of overtopping occurs when waves break on the upstream face of the dam and produce significant volumes of spume. These water droplets can then be carried over the crest under their own momentum as a result of wind. Another less important method of overtopping is in the form of spray generated by the action of strong wind on the wave crests but except in strong winds blowing onto the dam this spray will not contribute to any overtopping volume. Spray and spray volumes are not included in the surcharge results presented in this report.

## 7. Risk Assessment

### 7.1 Criteria

As expected from the fourteen reservoirs selected, no two dams are identical and few of the 14 are even similar, thus it is not possible to build up multiple statistics. A more useful and realistic measure of the potential existence of damage scenarios is the examination of the sensitive parameters of location, category, size, spillway type, run-up factors and age. Table 7.1 lists the reservoir criteria and the associated predicted changes in the total surcharge for the time horizon 2050 for each dam. The maximum, minimum and mean values for the predicted total surcharge in the 2050s were obtained from the interception of the total surcharge lines with the extreme right, left and centre points of the rectangle bounding the UKCIP98 scenarios (See Figures 7.1a,b&c).

### 7.2 Risk Assessment Framework

#### 7.2.1 Surcharge Predictions

Having established the maximum, minimum and mean predicted changes in total surcharge for winter and summer PMFs (or other relevant design flood inflow) it is possible to assess the winter versus summer values as a composite envelope for each site.

Figure 7.1a shows a plot of maximum predicted percentage change in total surcharge for winter against summer floods. The envelope of points is skewed at 45 degrees indicating similar values for predicted total surcharge for winter and summer floods. It is suggested that the risk span ranges three arbitrary zones of low, medium and high with two Welsh reservoirs at low risk and one Scottish at the high end of the spectrum, all others being of medium risk. On the other hand, using the minimum percentage prediction for total surcharge, Figure 7.1b, the gradient of the envelope is vertical and the risk is insignificant for this scenario. The mean of the percentage change in predictions for total surcharge shows a steep slope for the envelope indicating that the Y.axis (summer PMF % change in total surcharge) exhibits a larger range, Figure 7.1c.

In all three figures, Scottish reservoirs always appear at the high end of the spectrum associated with greater risk and south east England and/or Wales at the lower end, and associated with lesser risk.

| Reference No. | Location | Category | Size | Spillway Type | Run-up Factor | % Change in Total Surcharge (2050) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Maximum | | Minimum | | Mean Value | |
| | | | | | | Winter PMF | Summer PMF | Winter PMF | Summer PMF | Winter PMF | Summer PMF |
| 1 | Scotland | A | L | U | 1.44 | 7 | 8 | -4 | -1 | 1.5 | 3 |
| 2 | Scotland | A | M | U | 1.95 | 11 | 10 | -4 | -2 | 3 | 3.5 |
| 3 | Scotland | A | S | U | 1.55 | 9 | 7 | -2.5 | -1 | 3.5 | 3 |
| 4 | Scotland | C* | S | U | 1.66 | 7 | 7 | -2 | 0.5 | 3 | 4 |
| 5 | N.England | A | L | U | 1.54 | 9 | 8 | -2 | -3 | 3 | 3 |
| 6 | N.England | A | S | B | 1.34 | 9 | 7 | -2 | -7 | 3.5 | -0.5 |
| 7 | N.England | A | S | U | 1.33 | 8 | 6 | -2 | -7 | 3.5 | -0.5 |
| 8 | Wales | A | M | U | 1.34 | 7 | 5 | -1.5 | -9.5 | 3 | -2.5 |
| 9 | Wales | A | S | U | 1.55 | 4 | 3 | -1.5 | -4.5 | 1 | -1 |
| 10 | SW.England | A | M | B | 2.1 | 7 | 4 | -2 | -3 | 2.5 | -1.5 |
| 11 | SW.England | B# | S | U | 1.55 | 8 | 5 | -3 | -8.5 | 3 | -2 |
| 12 | SE.England | A | L | B | 1.7 | 7 | 6 | -3 | -14.5 | 2 | -4 |
| 13 | SE.England | A | M | U | 1.05 | 9 | 7.5 | -1.5 | -18.5 | 4.5 | -5 |
| 14 | SE.England | C* | S | U | 1.55 | 7.5 | 8 | -2.5 | -2 | 3 | -2 |

**Table 7.1 - Reservoir criteria and % change in Total Surcharge for the 2050s**

| Notes |
|---|
| Size - L - Large ( greater than 3km$^2$)<br>M - Medium (1 to 3km$^2$)<br>S - Small (less than 1km$^2$) |
| Spillway - U - Controlled |
| Type - B - Bellmouth |
| Run-up factor (Fig 6 - FRS) |

| |
|---|
| * denotes 1 in 10,000 Yr Flood |
| # denotes 1 in 1000 Yr Flood |

### 7.2.2 Risk Identification for maximum predicted % change in total surcharge for the 2050s.

Table 7.2 lists the assessment parameters for consideration of the significance of risk due to the percentage change in total surcharge.

Relationships were sought between the maximum percentage predictions of the total surcharge for the 2050s and geographic/climatic area, dam category, reservoir size, spillway type, wave run-up factor and age of dam.  The procedure was relatively subjective due to the process of selection and evaluation of the characteristics and no apparent relationships were demonstrated.  The relationships are included in Appendix G under figures 1 to 5 inclusive.

This lack of relationship between parameters is likely to be a function of sample size, complexity of the inter-actions, limited variability and the engineering judgement involved.

### 7.3 Summary

Changes in total surcharges help to define an assessment of the risk in the safety of the reservoirs.  The figures and tables summarise much of the findings.  In respect of the maximum, mean and minimum values for predicted total surcharge in 2050s, Scottish reservoirs always existed at the higher end of the spectra and south-east England and/or Wales at the lowest end.

No meaningful relationships were found between the maximum predicted percentage change in total surcharge (worst case chosen) for the 2050s and geographic/climatic area, dam category and age, reservoir size, spillway type and run-up factor due to limitations of the procedures.

| Reference No. | Location | Maximum % change in Total Surcharge | | Category | Size | Spillway Type | R.U. Factor | Age |
|---|---|---|---|---|---|---|---|---|
| | | Winter | Summer | | | | | |
| 1 | Scotland | 7 | 8 | 3 | 3 | 2 | 1.44 | 3 |
| 1 | Scotland | 11 | 10 | 3 | 2 | 2 | 1.95 | 3 |
| 1 | Scotland | 9 | 7 | 3 | 1 | 2 | 1.55 | 2 |
| 1 | Scotland | 7 | 7 | 1 | 1 | 2 | 1.66 | 1 |
| 2 | N.England | 9 | 8 | 3 | 3 | 2 | 1.54 | 3 |
| 2 | N.England | 9 | 7 | 3 | 1 | 1 | 1.34 | 3 |
| 2 | N.England | 8 | 6 | 3 | 1 | 2 | 1.33 | 2 |
| 3 | Wales | 7 | 5 | 3 | 2 | 2 | 1.34 | 3 |
| 3 | Wales | 4 | 3 | 3 | 1 | 2 | 1.55 | 1 |
| 4 | SW.England | 7 | 4 | 3 | 2 | 1 | 2.1 | 3 |
| 4 | SW.England | 7 | 5 | 2 | 3 | 2 | 1.55 | 1 |
| 5 | SE.England | 9 | 6 | 3 | 1 | 1 | 1.7 | 3 |
| 5 | SE.England | 9 | 7.5 | 3 | 2 | 2 | 1.05 | 3 |
| 5 | SE.England | 7.5 | 8 | 1 | 1 | 2 | 1.55 | 1 |

Category : 3 - Dam Category A
2 - Dam Category B
1 - Dam Category C

Spillway type : 2 - Uncontrolled spillway
1 - Bellmouth

Size - L - Large ( greater than $3km^2$)
M - Medium (1 to $3km^2$)
S - Small (less than $1km^2$)

Age : 3 - 1950 +
2 - 1900 - 1949
1 - pre 1900

* denotes 1 in 10,000 Yr Flood
# denotes 1 in 1000 Yr Flood

**Table 7.2 - Assessment parameters for significance of risk**

# 8 Conclusions and Recommendations

## 8.1 Conclusions

The approach followed was to assess the surcharge sensitivity of example reservoirs to incremental changes in the climatic factors affecting the design estimation of total surcharge. Fourteen example reservoirs were selected such that their design, hydro-climatic and geographical characteristics were reasonably representative of the characteristics of the overall population of British dams. The surcharge estimation procedure outlined in the third edition of the Floods and Reservoir Safety guide was followed. The key climatic attributes incrementally changed were: i) storm rainfall depth (in the estimation of flood surcharge), and ii) wind speed (in the estimation of wave surcharge). Other related climatic factors, such as storm profile, snowmelt and wind direction, were considered but until more is known about the likely effect of climate change on these it was considered premature to adjust them. The implications of the resulting site sensitivities could then be framed in terms of the currently available climate change projections.

The UK Climate Impact Programme takes as a baseline the years 1961 – 1990. It was considered reasonable to take the planning horizon for this report as the 2050s, by which time annual rainfall is predicted to increase across the UK with increases of about 5% in northern Britain and between 2 and 5% in southern Britain. This will be coupled with milder, wetter winters and warmer and drier summers in the south-east whilst the summers in the north-west are likely to be warmer and wetter. This will be coupled with milder, wetter winters and warmer, drier summers. Windspeed changes are predicted to be variable with small decreases in the South and slight increases in the North. The autumn and winter will become windier, while the spring and summer will become less so.

The study has considered the joint occurrence of the most extreme changes in both rainfall and wind speed at a set of reservoirs which provide a guide for the risk of occurrence and the risk to freeboard at any particular structure.

The study indicates that winter storm event rainfall (November – April) may increase within the range of 7-23% and winter wind speeds may increase by 1-4%. Similarly, summer storm event rainfall (May – September) may increase by 5-16% and summer wind speeds by 2-5%. In terms of total surcharge, winter surcharge changes could be in the range of 4-11% with summer values being in the range of 3-10%. No obvious regional pattern in terms of changes in total surcharge could be assessed from the analysis.

The results indicated that in a medium-high climate change scenario, the total surcharge at each of the reservoirs studied could increase by approximately 5%. This represented a change of between 40 and 270mm at the reservoirs analysed. If this is regarded as fairly representative of the impact in the 2050s of climate change on the UK stock of dams, then it seems likely that the most significant impact will be at the larger reservoirs, where the likelihood is that excess water will be retained by large dams.

Concrete and masonry dams should be able to withstand additional overtopping of the magnitude indicated by the study for the 2050s. However, the UK's stock of dams includes around 570 embankment dams that fall under the ICOLD definition of large dams (i.e. over 15m high) and many of these may be at risk from increases in flood surcharge. Many of these are already protected by wave or parapet walls and in such cases, the relatively modest increases in surcharge predicted may not have a significant impact on the structures, other than to increase the length of time where erosion to wave overtopping and wave slop will be required. In the case of embankment dams without a wave wall or a parapet wall, the situation may be different and the potential for erosion of the crest could be greater. Analysis indicates that around 50 of the UK's stock of dams could be affected in this way.

The dams analysed were too diverse to provide any meaningful statistical analysis of the results. However, it seems likely that reservoirs in Scotland will be subjected to greater changes in freeboard requirement than those in the south east of England and Wales, which fall in the areas of lower risk in the climate change models.

Climate change is only one of a number of impacts which is likely to effect the UK stock of dams over the next fifty years. Design standards will change for reservoirs and it is possible that a more risk based approach will be introduced to assessing dam safety. Further research is being carried out in a number of areas which will have an impact on the freeboard calculations. While these are complementary to the further research being undertaken on climate change within the UK and globally, all such aspects need to be considered when reviewing future improvement works for reservoir overflow provision.

### 8.2 Recommendations

It is recommended that consideration be given by DETR, now DEFRA, to the following in respect of the conclusions reached within this report.

a) An early review based on the UKCIP02 scenarios that are due to be released in 2002.

(b) Supervising engineers should be made aware of the need to assess the impact of weather patterns on the reservoirs for which they are responsible and to bring to the attention of the Inspecting Engineers any peculiar incidents that have occurred in terms of the climate over the period since the previous inspection. It is suggested that one way this could be undertaken is to include it as one of the areas highlighted for review by the Supervising Engineer within the Guide to the Reservoirs Act 1975.

c) In any further work being undertaken by DEFRA on floods and reservoir safety integration, climate change should be clearly identified as one of the areas of risk for the future. It may be appropriate to add a section to any fourth edition of Floods & Reservoir Safety regarding the need for consideration of climate change aspects to be taken into account when assessing future freeboard requirements at a reservoir.

d) This report should be made available to the reservoir profession through the DETR's, now DEFRA's, website or some similar appropriate format. In particular, the fourteen reservoirs which were analysed give within the graphical representation of percentage changes in storm depth to percentage changes in windspeed, a useful indication of climate impacts in different parts of the country. However, it must be emphasised that each case will be individual, so no precise conclusions can be drawn from the studies carried out in relation to a specific reservoir in any region, although the sample selected will give an indication of response from key types of reservoir.

   Recognising the scale of the changes in total surcharge indicated it is suggested that Panel Engineers check for sensitivity to increases of 1-2% in total surcharge in the 10 year period between statutory inspections.

   Also, if freeboard is inadequate for other reasons and upgrading work is required, consideration should be given to adding a 50 year margin in the range 5-10% for climate change effects. The presentation of the plots for the UK 2050 medium high scenario will, however, give a good indication of likely changes in rainfall and windspeed in any particular region.

## Figures


| | |
|---|---|
| 3.1 | Geographical location of representative dams |
| 4.1 | Global Climate Model (UK cells) |
| 4.2 | Annual Precipitation |
| 4.3 | Seasonal precipitation changes |
| 4.4 | Wind Speeds (daily average) |
| 4.5 | Wind Speeds (seasonal changes) |
| 4.6 | Changes in precipitation/wind |
| 7.1 | Surcharge changes (max/min/ mean) |

Note
1.Refer also to Table 3.1
2.Selection excludes Northern Ireland

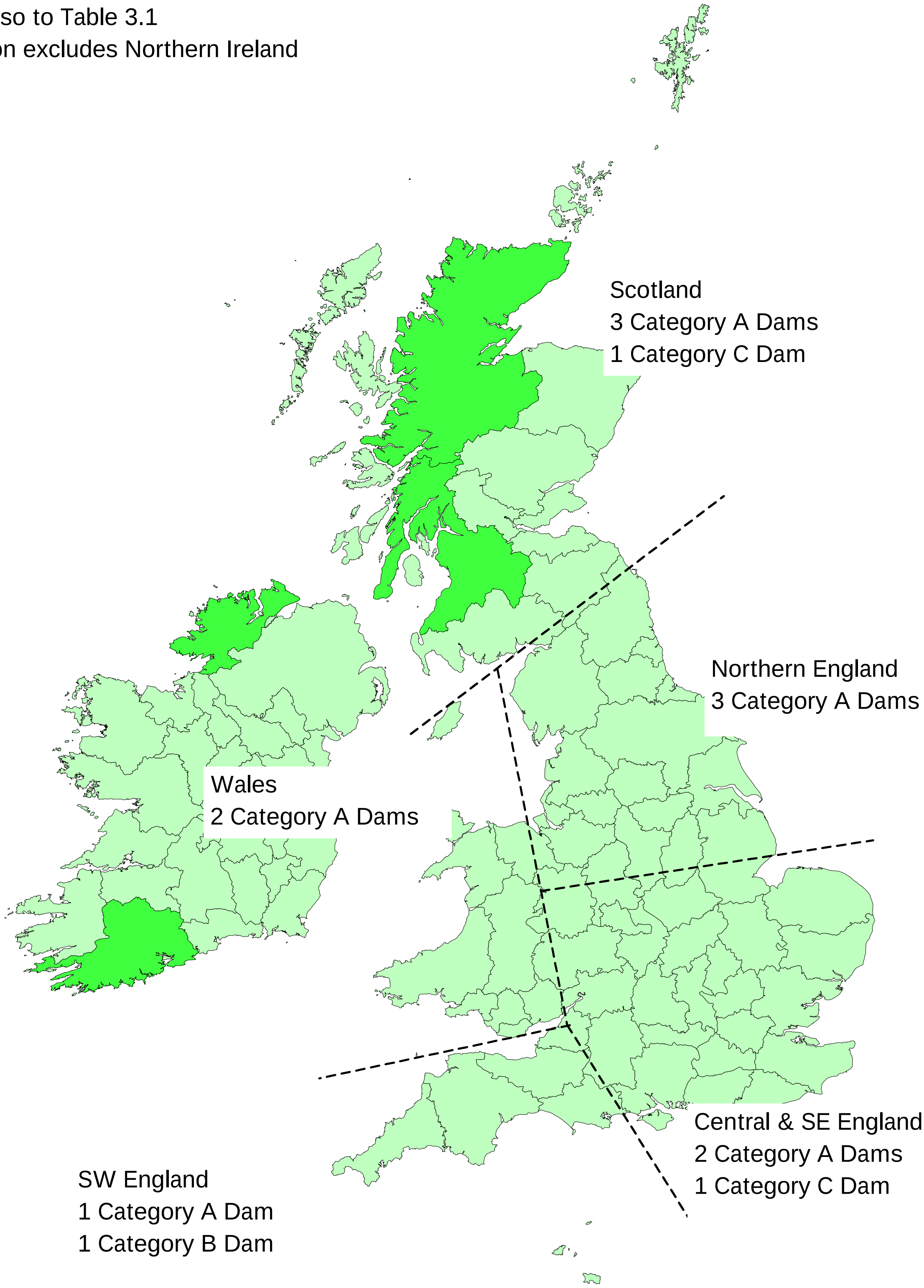


**Figure 3.1 - Geographical Location of Representive Dams**

**Figure 4.1** – Grid of HadCM2 of the Hadley Centre Global Climate Model (GCM) Cells Over the UK.

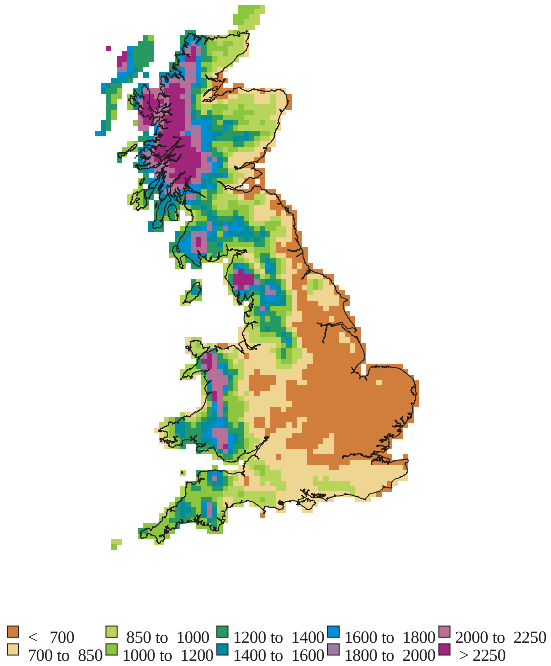


***Figure 4.2a****.Annual precipitation for the 1961-1990 baseline period*

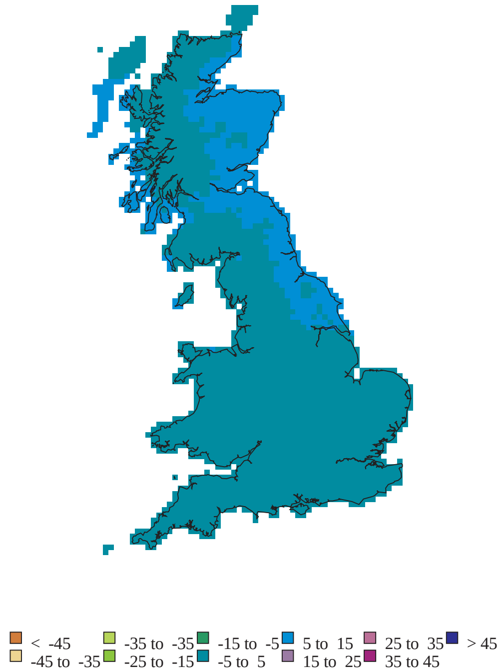


***Figure 4.2b****.Average annual percentage change in thel precipitation for the 2050s under the UKCIP98 medium-high scenario*

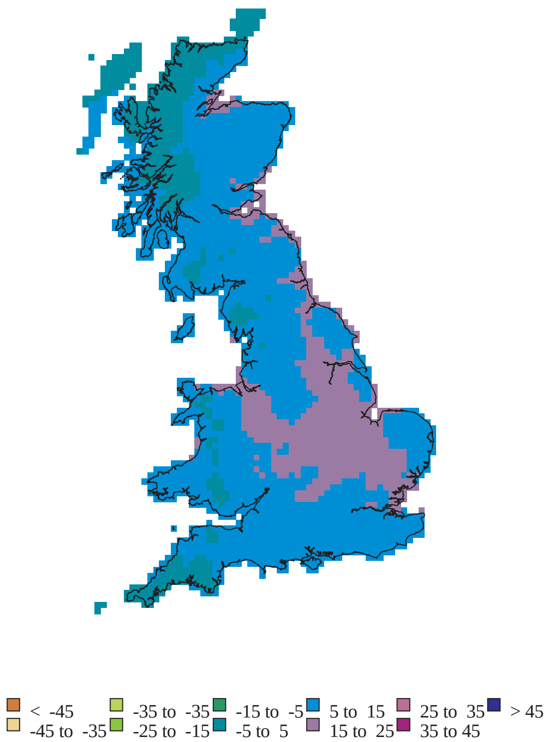


***Figure 4.3a***. *Percentage change in the average January precipitation for the 2050s under the UKCIP98 medium-high scenario.*

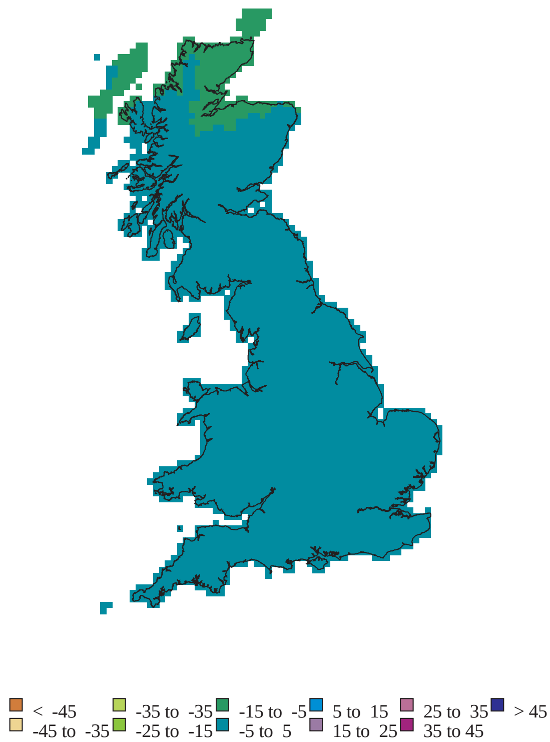


***Figure 4.3b***. *Percentage change in the average April precipitation for the 2050s under the UKCIP98 medium-high scenario.*

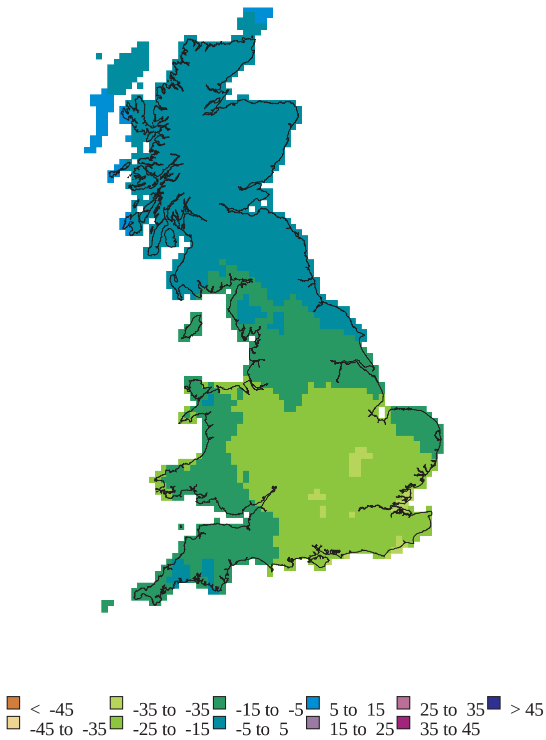


***Figure 4.3c***. *Percentage change in the average July precipitation for the 2050s under the UKCIP98 medium-high scenario.*

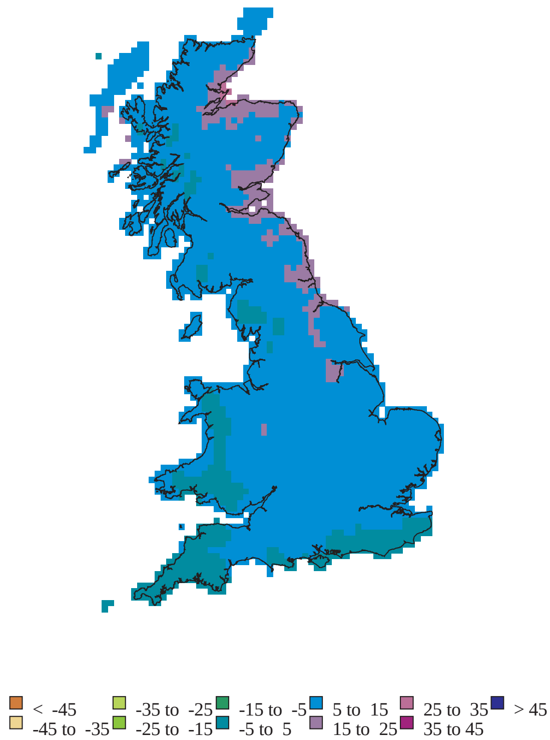


***Figure 4.3d***. *Percentage change in the average October precipitation for the 2050s under the UKCIP98 medium-high scenario.*

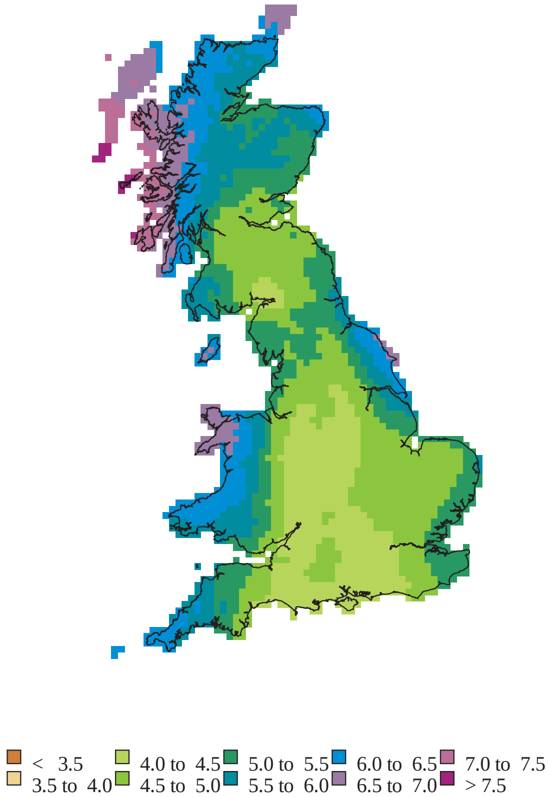


***Figure 4.4a*** *Wind speed (daily average) for the 1961-1990 baseline period*

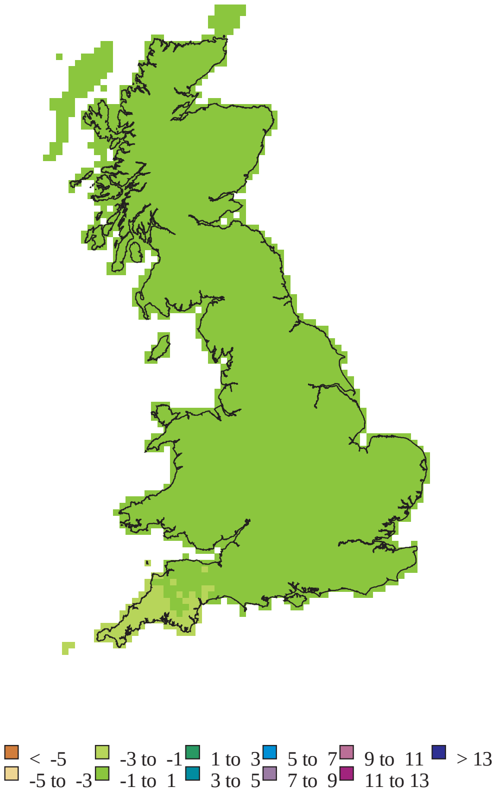


***Figure 4.4b****. Average annual percentage change in daily wind speed for the 2050s under the UKCIP98 medium-high scenario.*

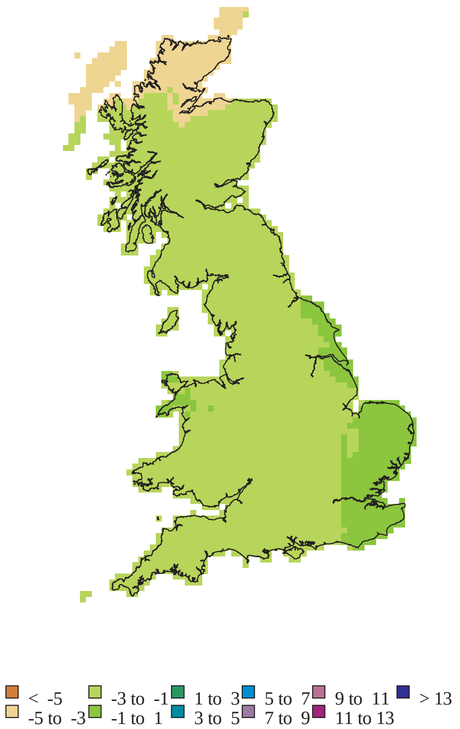


***Figure 4.5a***. *Percentage change in the average January wind speed for the 2050s under the UKCIP98 medium-high scenario.*

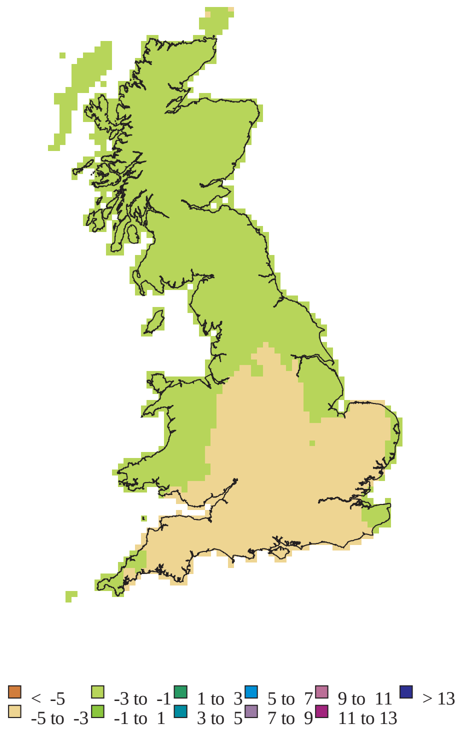


***Figure 4.5b***. *Percentage change in the average April wind speed for the 2050s under the UKCIP98 medium-high scenario.*

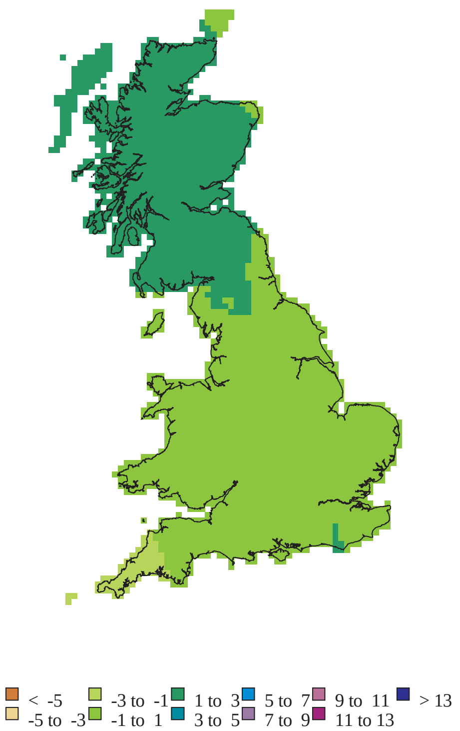


***Figure 4.5c***. *Percentage change in the average July wind speed for the 2050s under the UKCIP98 medium-high scenario.*

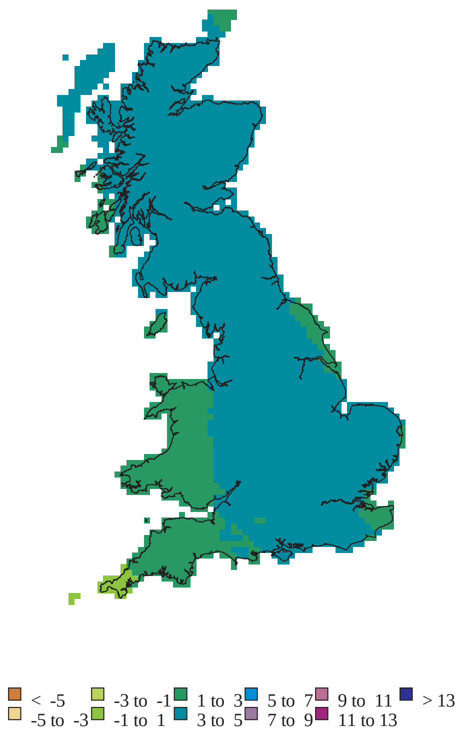


***Figure 4.5d***. *Percentage change in the average October wind speed for the 2050s under the UKCIP98 medium-high scenario.*

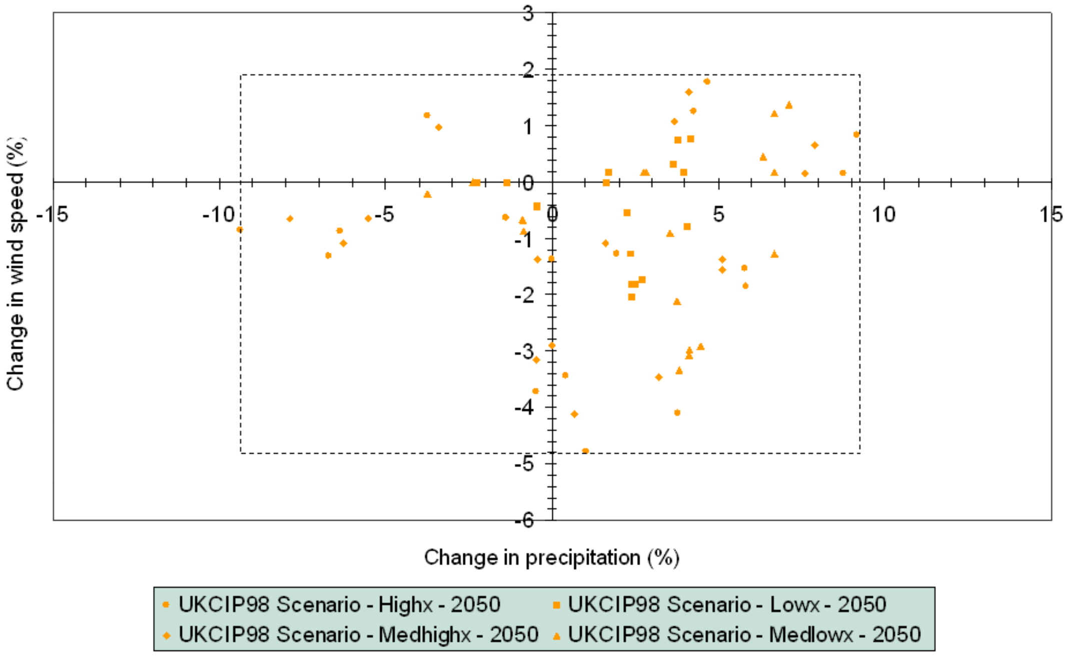


***Figure 4.6***. *Monthly changes in precipitation wind speed for all available scenarios for the 2050s time horizon for one reservoir.*

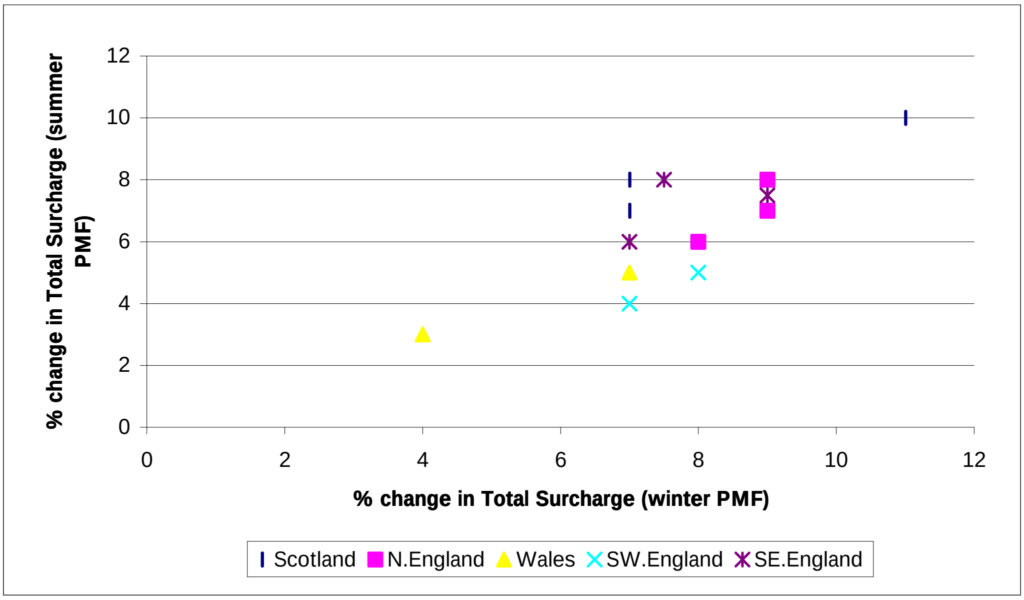


Figure 7.1a: Association between winter and summer PMF's for the maximum predicted % change in Total Surcharge ( Time Horizon 2050s )

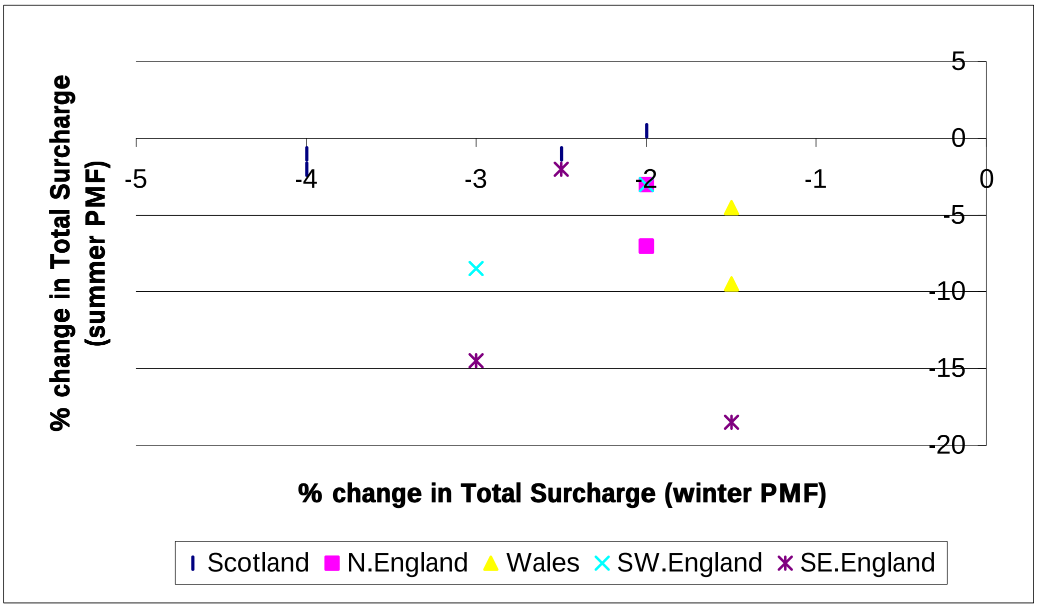


Figure 7.1b : Association between winter and summer PMF's for the minimum predicted % change in Total Surcharge (Time Horizon 2050s)

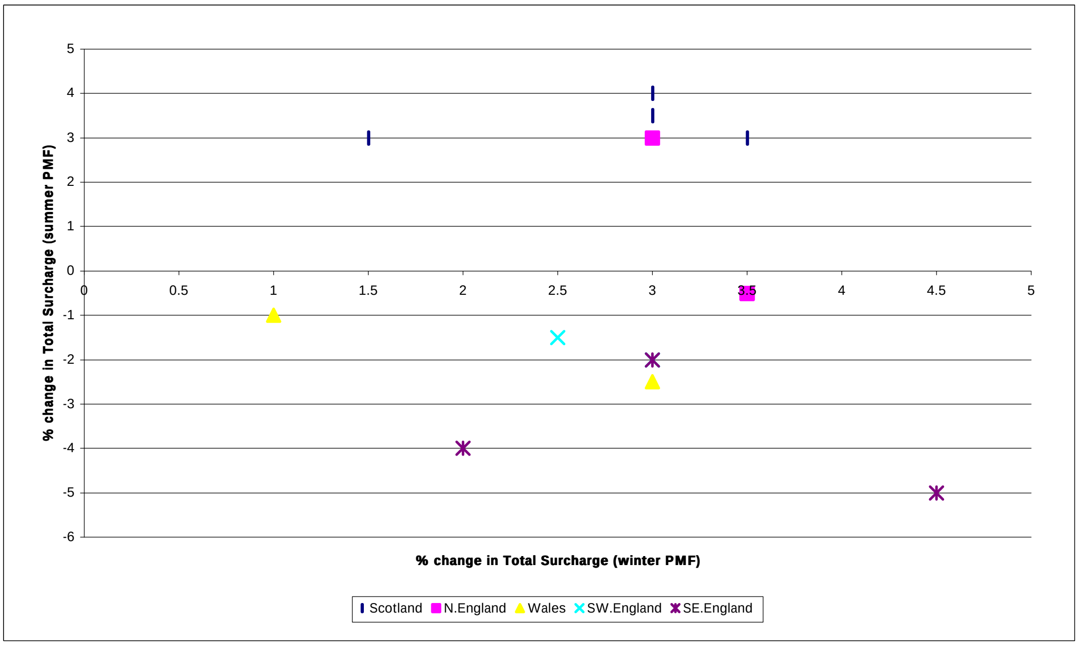


Figure 7.1c : Association between winter and summer PMF's for the mean value % change in Total Surcharge (Time Horizon 2050)

# Appendix A

## References

## Appendix A - References

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## Appendix B

## Glossary of Terms

## Appendix B - Glossary of Terms

Several terms used are peculiar to or most often used in rather specialist technical disciplines. Others are used in special, restricted senses. Some such terms are defined when first used; others are not. For convenience of the reader a number of those technical terms are defined here.

| | |
|---|---|
| **B R E** | Building Research Establishment Ltd |
| **Crest of Dam** | As top of dam |
| **Dam** | A barrier built across a watercourse for impounding or diverting the flow of water. |
| **Design Flood** | The hydrograph of the flood inflow to the reservoir which produces the maximum level of the reservoir which the dam is designed or required to accept without fundamental structural damage. |
| **Earthfill Dam** | An embankment dam in which more than 50 percent of the total volume is formed of compacted fire grained material obtained from a borrow area. Type TE or 1 is the category used for Earth Fill based on the World Register. |
| **FEH** | Flood Estimation Handbook |
| **Fetch** | The maximum uninterrupted straight line length over water ignoring promontories for a particular wind direction. The direction of fetch is always away from the dam. |
| **Flood Routing** | The determination of the modifying or attenuating effect of passage of a flood through a valley, channel, or reservoir. |
| **Flood Surcharge** | The maximum rise of still water level above reservoir top water level (or retention water level) during a design flood. (Flood surcharge water is not retained in the reservoir but is discharged until the normal retention level is reached). |
| **Freeboard, dam** | The vertical height from top water level (or retention water level) to the top of the dam. |

| | |
|---|---|
| **FRS** | Floods and Reservoir Safety Guide. 3rd Edition published in 1996. |
| **FSR** | Flood Studies Report originally published by the Natural Environment Research Council in 1975. |
| **G C M** | Global Climate Model |
| **Hazard** | A source of danger. In other words, something that has the potential for creating adverse consequences. |
| **HOST** | Hydrology of Soil Types |
| **Hydrograph** | A graphical representation of discharge, stage, or other hydraulic property with respect to time for a particular point on a stream (At times the term is applied to the phenomenon the graphical representation describes; hence, a flood hydrograph is the passage of a flood discharge past the observation point). |
| **Maximum Water Level** | The maximum stillwater level of the design flood. |
| **Overtopping** | Water flowing over the top of the dam, other than over spillweirs or crests. |
| **Parapet Wall** | A solid wall located or placed on the upstream (and/or downstream) edge(s) of the top of the dam section. Used to protect vehicular and pedestrian traffic across the dam. |
| **Probability** | The likelihood of an event occurring. |
| **Probable Maximum Flood (PMF)** | The flood hydrograph resulting from PMP and , where applicable, snowmelt, coupled with the worst flood-producing catchment conditions that can be realistically expected in the prevailing meteorological conditions. |

| | |
|---|---|
| **Probable Maximum Precipitation (PMP)** | The (theoretical) greatest depth of precipitation for a given duration meteorologically possible for a given basin at a particular time of year. It includes rain, sleet, snow and hail as it occurs, but not snow cover left from previous storms. |
| **Rainfall event depth** | Total depth of rainfall falling during the storm event |
| **Rainfall event profile** | The magnitude and sequence of precipitation in equal time increments during a storm of given duration. |
| **Reservoir Flood Routing** | The passage of a flood volume through a reservoir. Generally used to describe the calculation of the attenuation of the hydrograph of the incoming flood as it passes through storage and down the spillway. |
| **Return period** | The average expected time (in terms of probability rather than forecasting) between floods equal to or greater than a stated magnitude. |
| **Rip-rap** | A layer of large random stones, or broken rock, usually placed on a graded filter. |
| **Risk** | The likelihood of adverse consequences. |
| **Risk Assessment** | As applied to dam safety, the process of identifying the likelihood and consequences of dam failure to provide the basis for informed decisions on a course of action. |
| **Run-up** | The maximum vertical height attained by a wave running up a dam face, relative to the stillwater level without wind action. |
| **SAAR** | Standard Average Annual Rainfall (1941-1970). |
| **Significant wave height** | The wave height, trough to crest, that is exceeded by only a small stated percentage of waves. |
| **SPR** | Standard Percentage Run-off. |

| | |
|---|---|
| **Stillwater Level** | The water level in the absence of any wave effects. |
| **Spillway** | A structure over or through which flood flows are discharged. If the flow is controlled by gates, it is considered a controlled spillway; if the elevation of the spillway crest is the only control, it is considered an uncontrolled spillway. |
| **Spillway Design Flood (SDF)** | The largest flood that a given project is designed to pass safely. |
| **Top of dam** | The top level of the dam structure. (Can be the top of the wave wall if the wall is solid from abutment to abutment, without openings and considered able to withstand potential wave or water loading). |
| **Top water level** | (a) for a reservoir with a fixed overflow sill, the lowest crest level of that sill;<br>(b) for a reservoir from which the overflow is controlled wholly or partly by movable gates, siphons or other means, the maximum level at which water may be stored exclusive to any provision for flood storage.<br>At this level the reservoir is "just full" without overflowing. |
| **Total surcharge** | The maximum level assessed of the flood surcharge level surmounted by the wave surcharge. |
| **UKCIP** | United Kingdom Climate Impacts Programme |
| **Unit Hydrograph (UH)** | The run-off hydrograph resulting from unit volume of rainfall excess in a specified duration of time over a given catchment; the rainfall is presumed to fall uniformly or characteristically in both time and space on the catchment in the specified duration. |
| **Wave set-up** | The height resulting from mass movement of water due to waves, by which the mean level of the water surface at the dam exceeds the mean water level of the reservoir. |

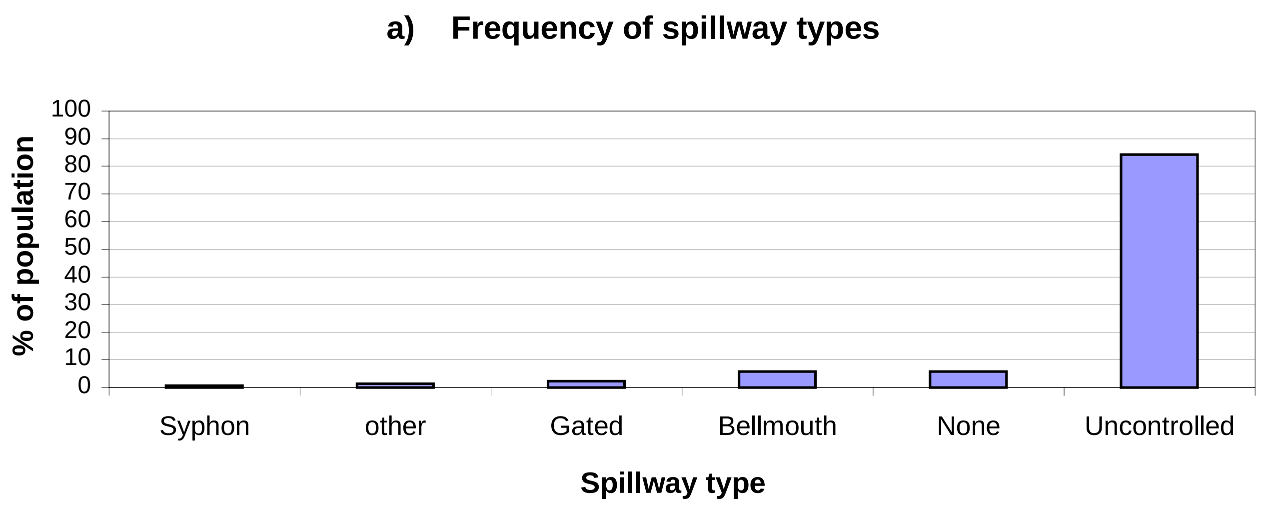
| | |
|---|---|
| **Wave surcharge** | The rise of water against a dam created solely by the run-up of waves of specified probability. |
| **Wave surcharge allowance** | For the particular type and design of dam, the theoretical component of the flood freeboard sufficient to prevent overtopping by waves reaching quantities that could threaten the dam. |
| **Wave wall** | A solid wall built along the upstream side of the crest of a dam and designed to withstand or reflect waves |

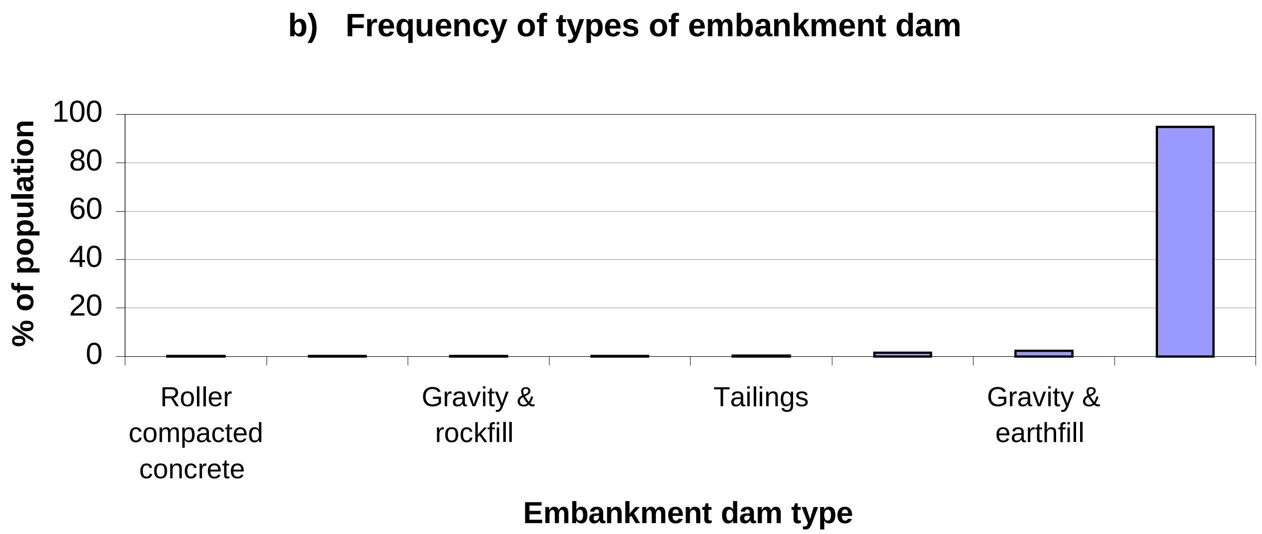
## Appendix C

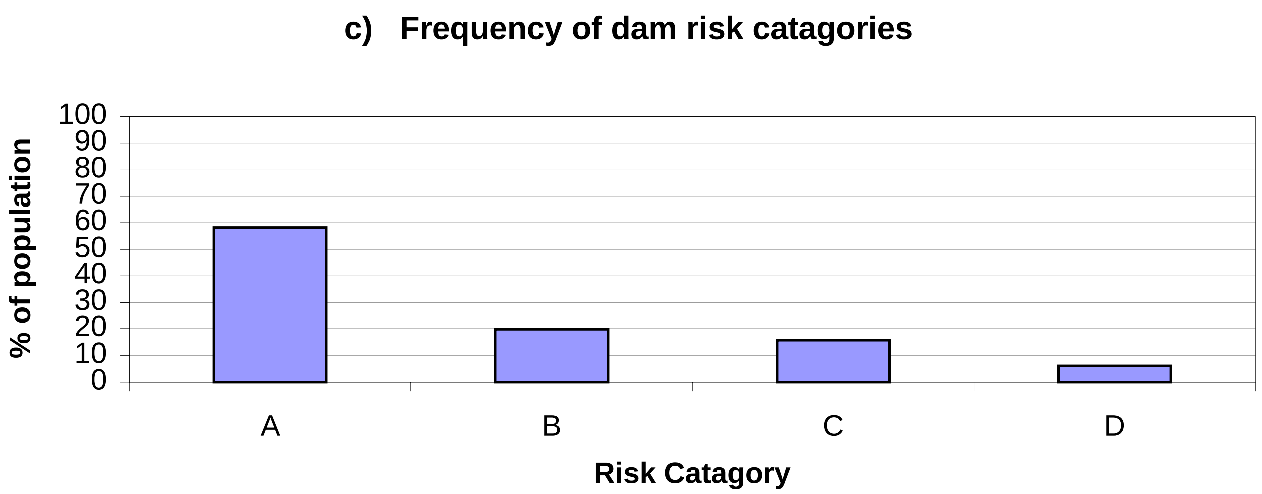
## British Dam population characteristics obtained from the BRE

## Appendix C - British Dam Population Characteristics

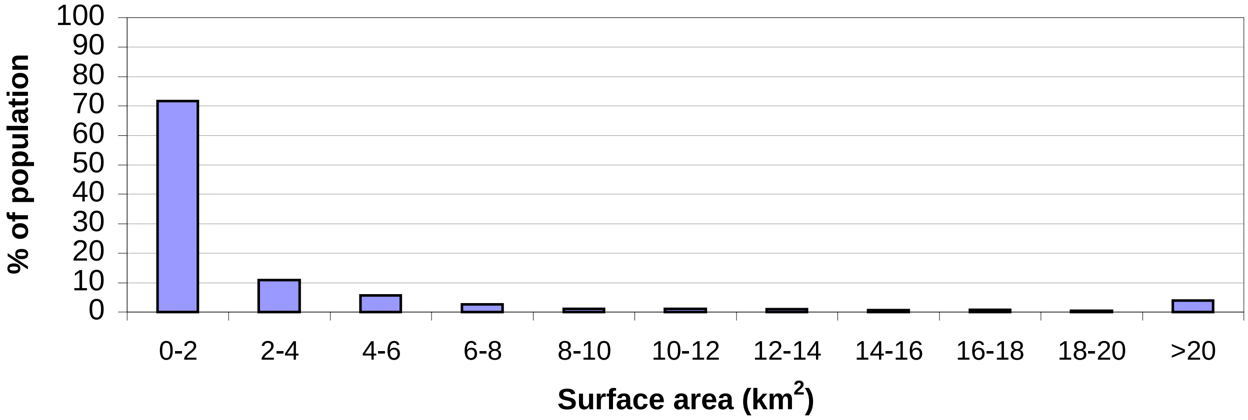
The BRE dams database was used to help identify a subset of broadly representative embankment dams for the purposes of the project. Figures C.1 a) - e) graphically show the population characteristics for those attributes considered useful in this selection process. Characteristics such as fetch, catchment area and average annual rainfall, which would be useful to this project, are not kept within the database.


a) Frequency of spillway types
% of population
100
90
80
70
60
50
40
30
20
10
0
Syphon
other
Gated
Bellmouth
None
Uncontrolled
Spillway type

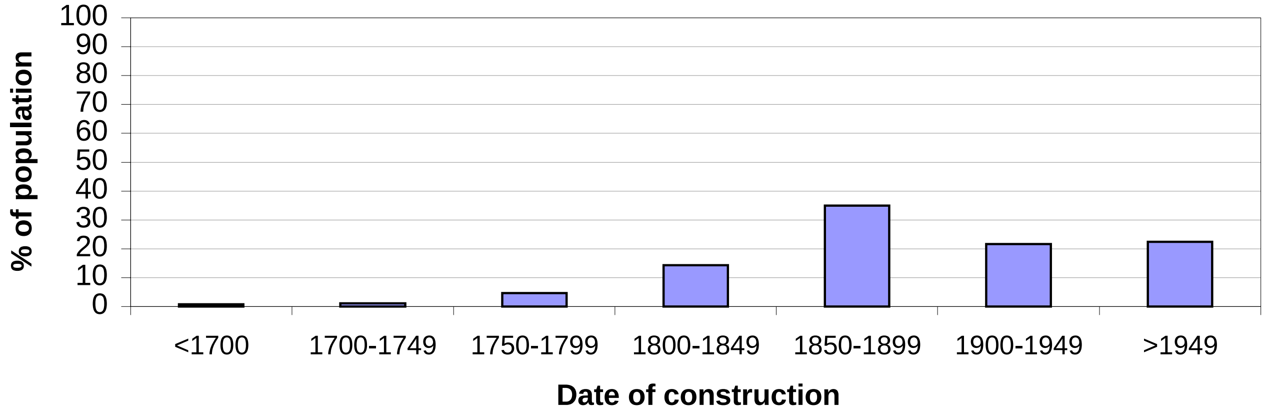

b) Frequency of types of embankment dam
% of population
100
80
60
40
20
0
Roller compacted concrete
Gravity & rockfill
Tailings
Gravity & earthfill
Embankment dam type


c) Frequency of dam risk catagories
% of population
100
90
80
70
60
50
40
30
20
10
0
A
B
C
D
Risk Catagory

## d) Reservoir surface area distribution




## e) Age distribution



## Appendix D

## The Implications of using the Flood Estimation Handbook for Reservoir Flood Studies

## Appendix D - Implications of using the Flood Estimation Handbook for reservoir flood studies

The Flood Estimation Handbook was published in December 1999. The FEH research programme was principally aimed at improving flood frequency estimation for river flood design and was not funded by DETR. In consequence, the research did not set out to explicitly amend or upgrade methods of reservoir flood estimation. In particular, the FEH leaves most elements of the FSR rainfall-runoff method unchanged. Nevertheless, the FEH has introduced some important changes which touch on reservoir flood safety applications. These are now elaborated.

Volume 2 of the Flood Estimation Handbook (Faulkner, 1999) presents a new general procedure for rainfall depth-duration-frequency estimation in the UK. As stated, the FEH research was not directed at improving estimations for design rainfalls and floods of the very longest return period, such as the 10000-year events relevant in many reservoir flood safety assessments. However, the method as published can be used to derive 10000-year, 1000-year and 192-year design rainfall depths that are relevant in reservoir flood safety assessments. These design rainfall estimates differ from those given in the Flood Studies Report. As discussed in detail in a recent companion report to DETR (Babtie, 2000), design rainfall estimates by the FEH and FSR procedures differ principally because of the different methodologies used. Because the FEH estimates are, in many cases of relevance to reservoir safety, significantly greater than their FSR counterparts, there is legitimate concern as to whether the FEH procedure should be adopted in UK reservoir flood assessments. This topic is beyond the scope of the current report.

A less contentious change introduced by the FEH concerns the new methods provided for estimating key parameters of the rainfall-runoff method. In particular, software accompanying the FEH allows users to derive estimates of standard percentage runoff (SPR) based on 1:250000 soil maps (in Great Britain) and the HOST classification of soil types (Boorman *et al.,* 1995). In addition, the user is now able to estimate the key catchment response time, Tp, from digital map data (Marshall, 2000; Bayliss, 1999). These new estimation methods for components of the FSR rainfall-runoff method are thought to provide useful refinements, and it is anticipated that most will be routinely adopted in reservoir flood safety assessments. Such improvements are based on an analysis of gauged data. Few reservoired catchments are gauged and, because the size (in particular), wetness and soils of UK reservoired catchments are *"off-centre"* to those of UK gauged catchments (see Table 3.1 of Reed and Field, 1992), the overall effect of these changes is difficult to judge.

A particularly helpful change introduced in the FEH is the comprehensive technical re-write of the rainfall-runoff method given in Volume 4 (Houghton-Carr), 1999). This helps the new user to understand both the principles and the detail of the FSR rainfall-runoff method (and its many updates in the 1980s) with greater clarity. In addition, Houghton-Carr draws attention to some of the research that has taken place on related matters. The probable maximum precipitation (PMP) estimation and probable maximum flood (PMF) estimation are of particular concern to reservoir flood safety.

Reference is made in Volume 4 to research by Salford University and the Met. Office (Austin *et al.*, 1995; Collier and Hardaker, 1996) to develop new ways of estimating PMP and PMF. It should be noted that these new procedures have not been generalised. Thus, it was not possible for the FEH to present new generalised procedures for PMP and PMF estimation. In consequence, it is anticipated that most PMF assessments for reservoir flood safety will continue to use PMP estimates given in the FSR (NERC, 1975).

Chapter 10 of FEH Volume 1 (Reed, 1999) presents a brief resume of factors to be borne in mind when estimating flood frequency in support of public safety. Chapter 7 of that volume provides a general discussion of climate change issues related to flood frequency. Finally, Appendix B of that volume presents a detailed review of methodologies used to solve so-called "*joint probability*" problems. From this it is possible to gain a clear understanding of why research to develop more formal solutions to the joint probability problems faced in reservoir flood safety assessment (eg. snowmelt plus rainfall, flood surcharge) was inconclusive. The main difficulty again lies in the inability to generalise specialised research methods.

# Appendix E

## Summary Climate Change Scenarios

## Appendix E - Summary Climate Change Scenarios

For each site the following information is given:

- Monthly percentage changes in mean daily wind speed and average monthly precipitation as predicted by the UKCIP98 scenarios of various sensitivity emissions for the time horizon 2050s. Seasonal and annual changes are also shown in the graphs.
- Sensitivity range as defined by the combined maximum/minimum monthly changes predicted by the climate change scenarios. This is done for the winter season (November to April) and the summer season (May to October).

The derived envelopes are also included in the charts in Appendix F to indicate the scale of potential climate change relevant to a particular reservoir site.

<u>Reservoir No.1 - Scotland</u>

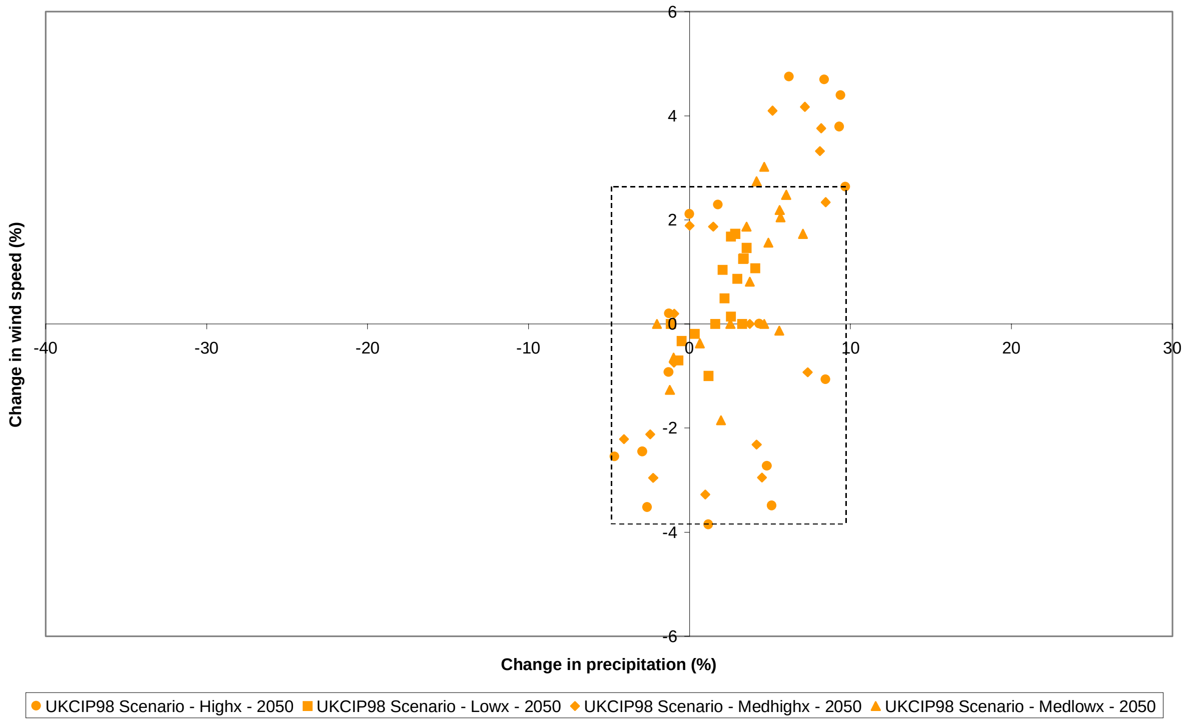



***Figure a**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

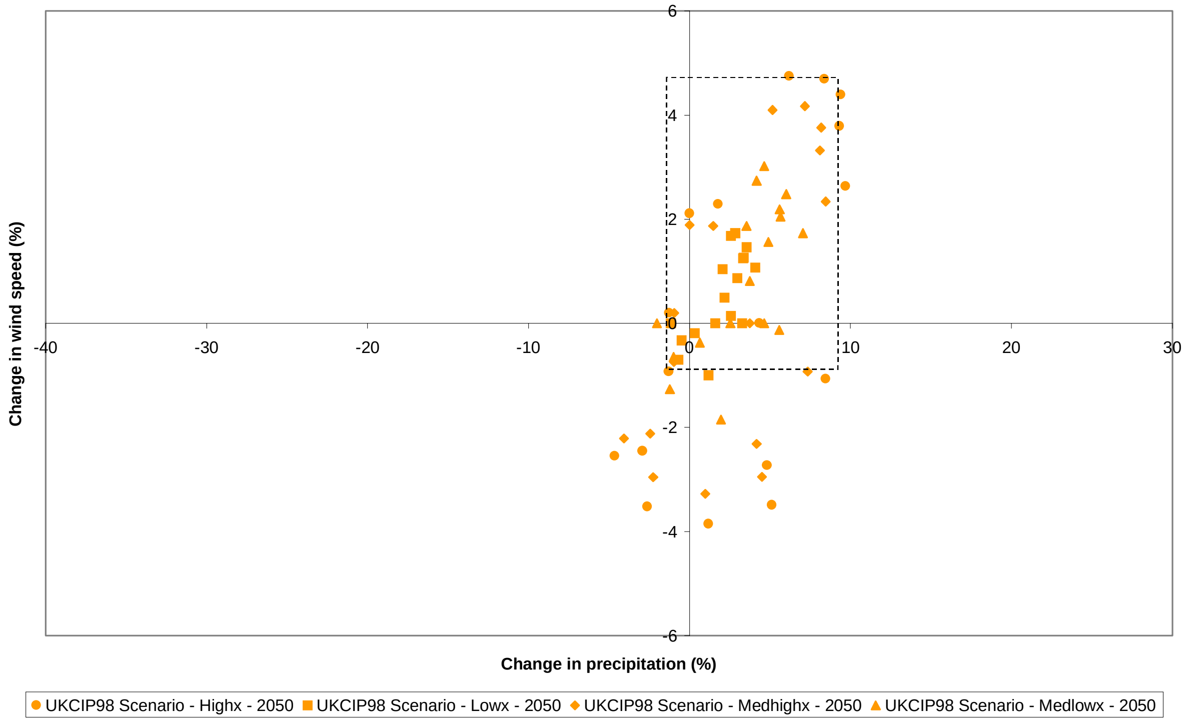



***Figure b**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

## Reservoir No.2 - Scotland

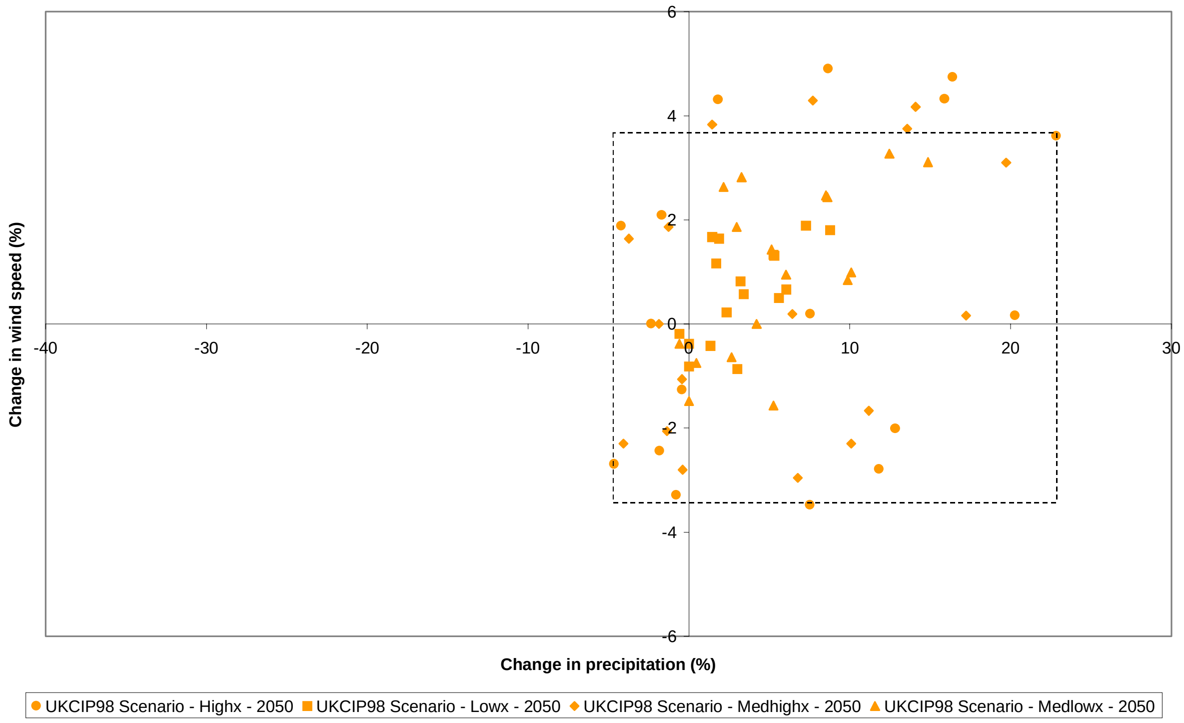



***Figure a***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

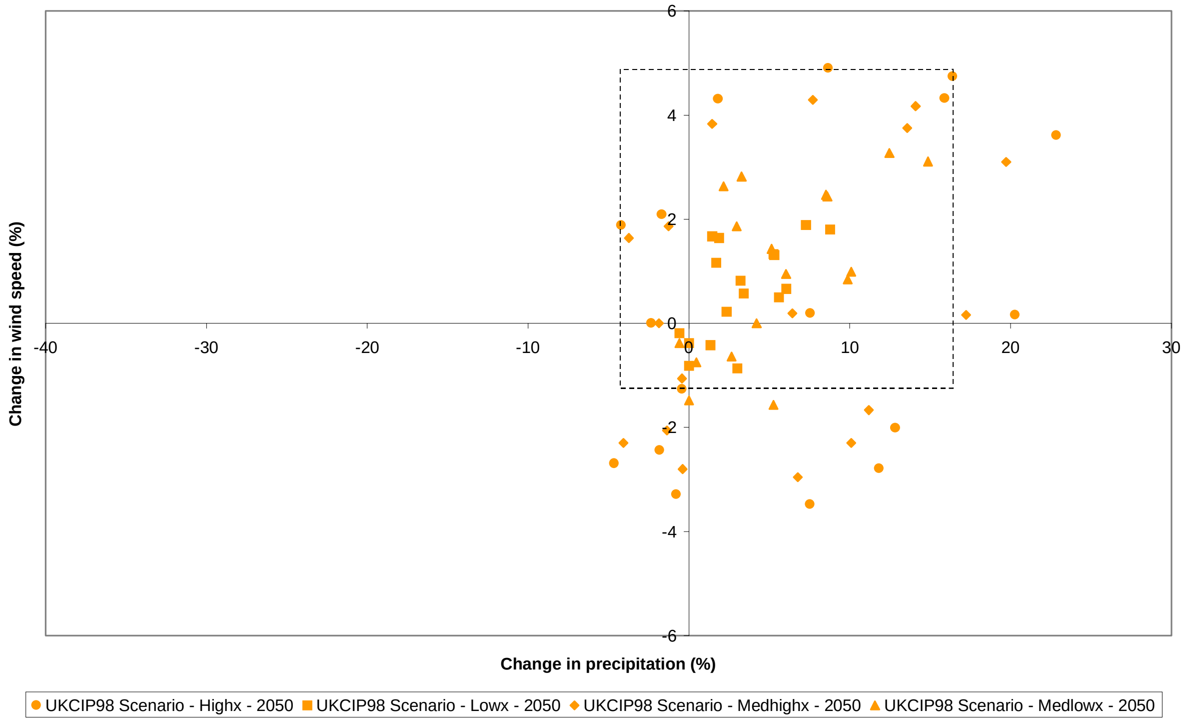



***Figure b***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

<u>Reservoir No.3 - Scotland</u>

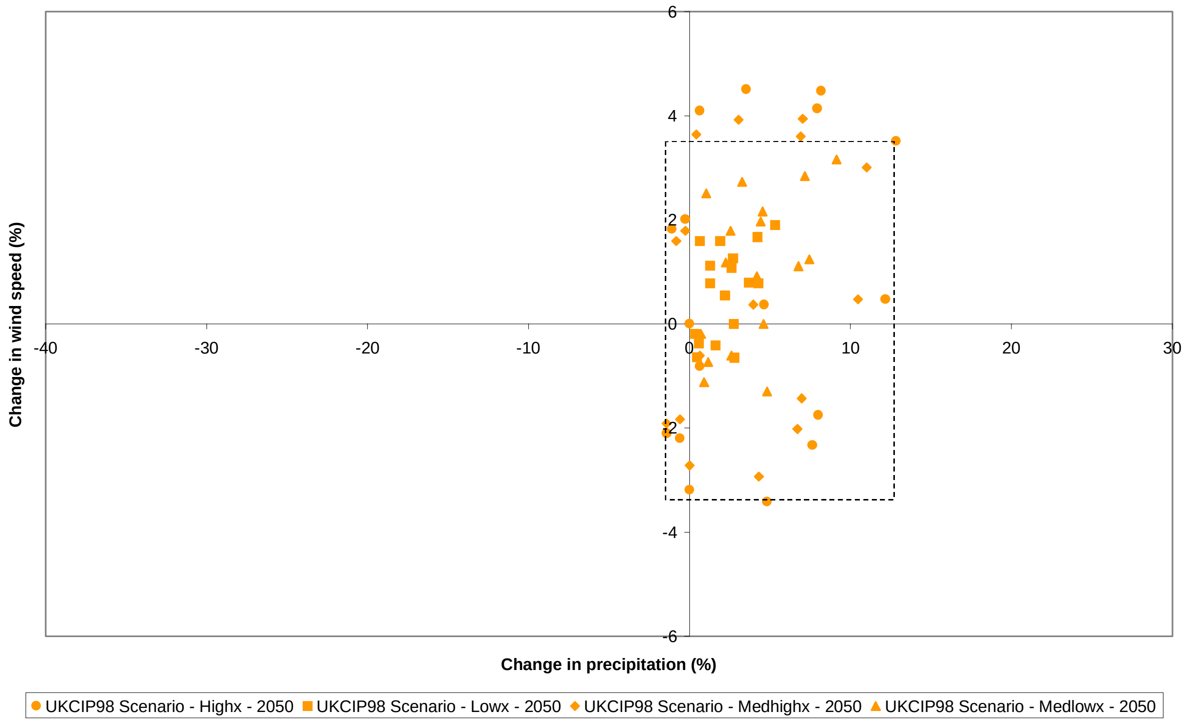



***Figure a**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

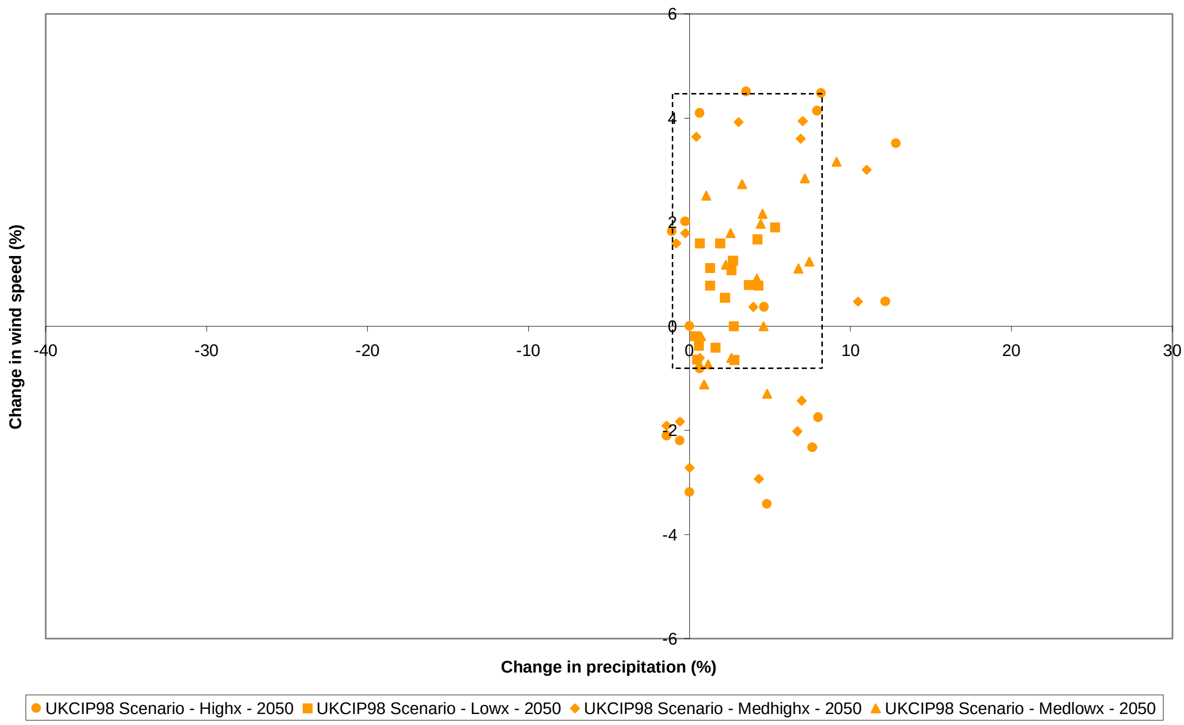



***Figure b**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

<u>Reservoir No.4 - Scotland</u>

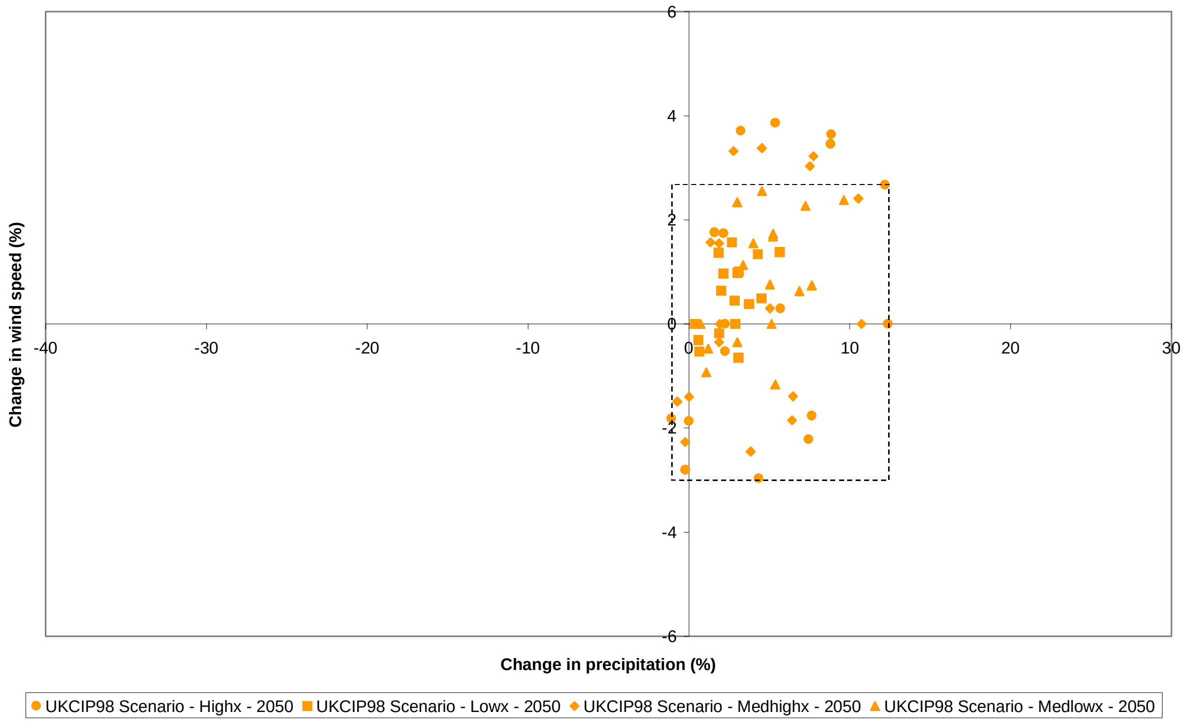



***Figure a**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

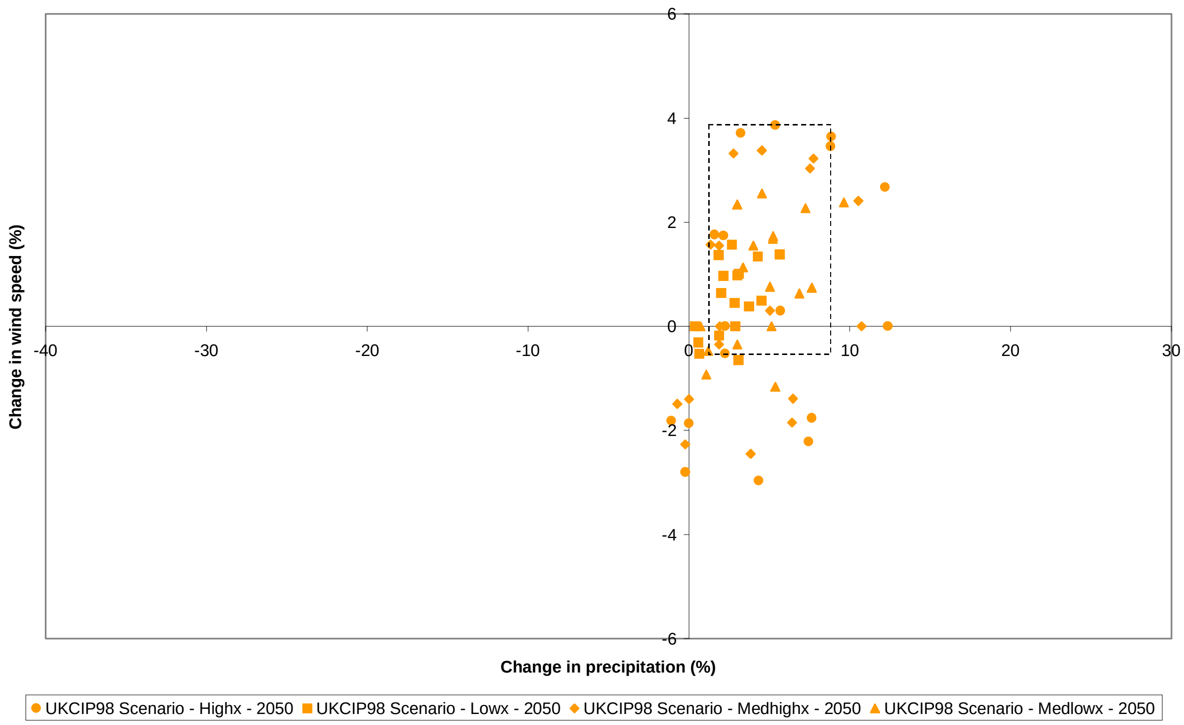



***Figure b**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

# Reservoir No.5 – North England

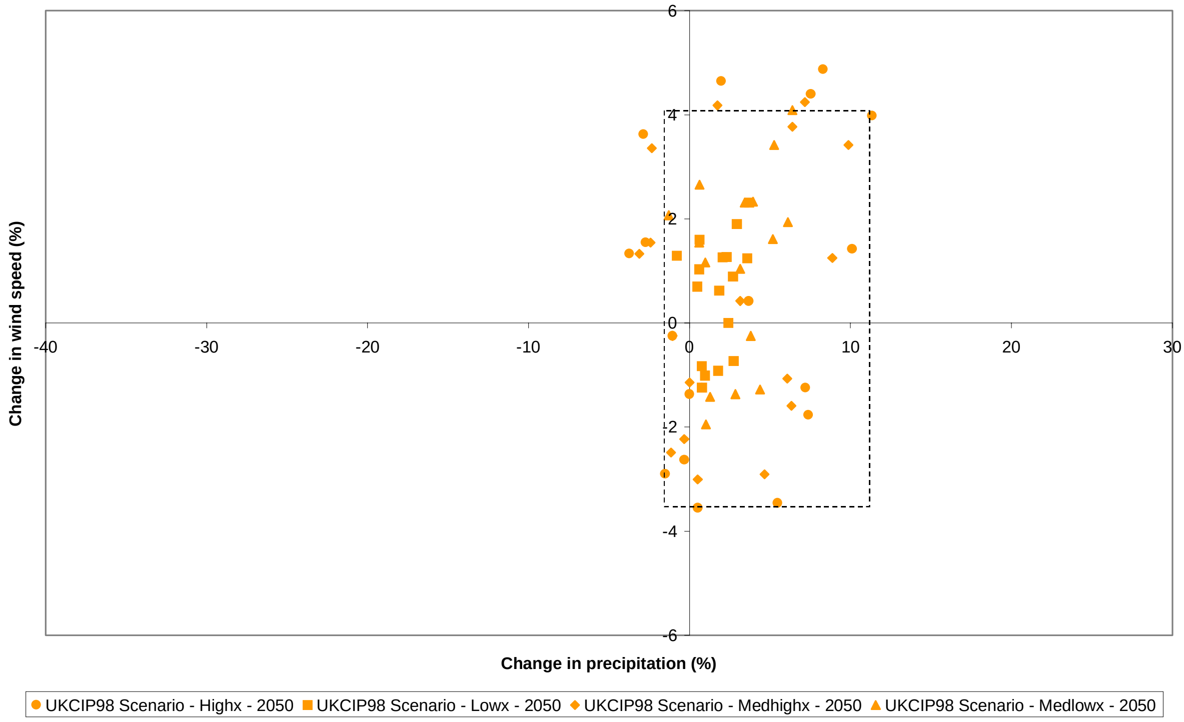



***Figure a****: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

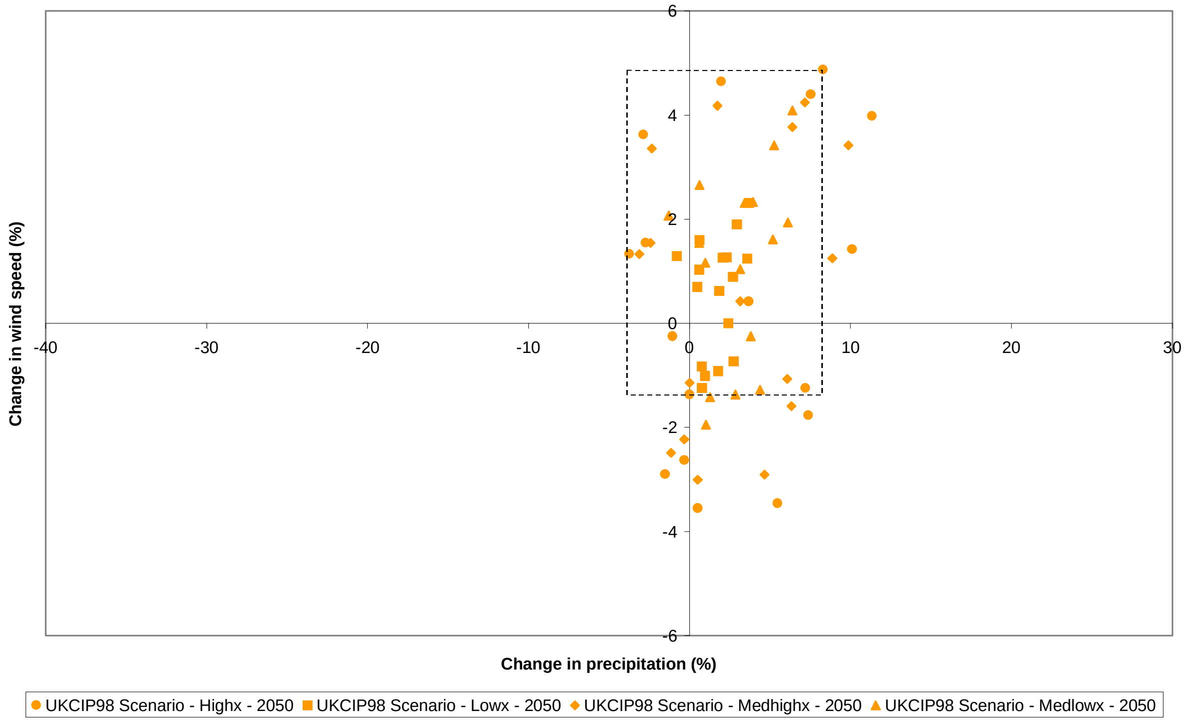



***Figure b****: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

<u>Reservoir No.6 – North England</u>

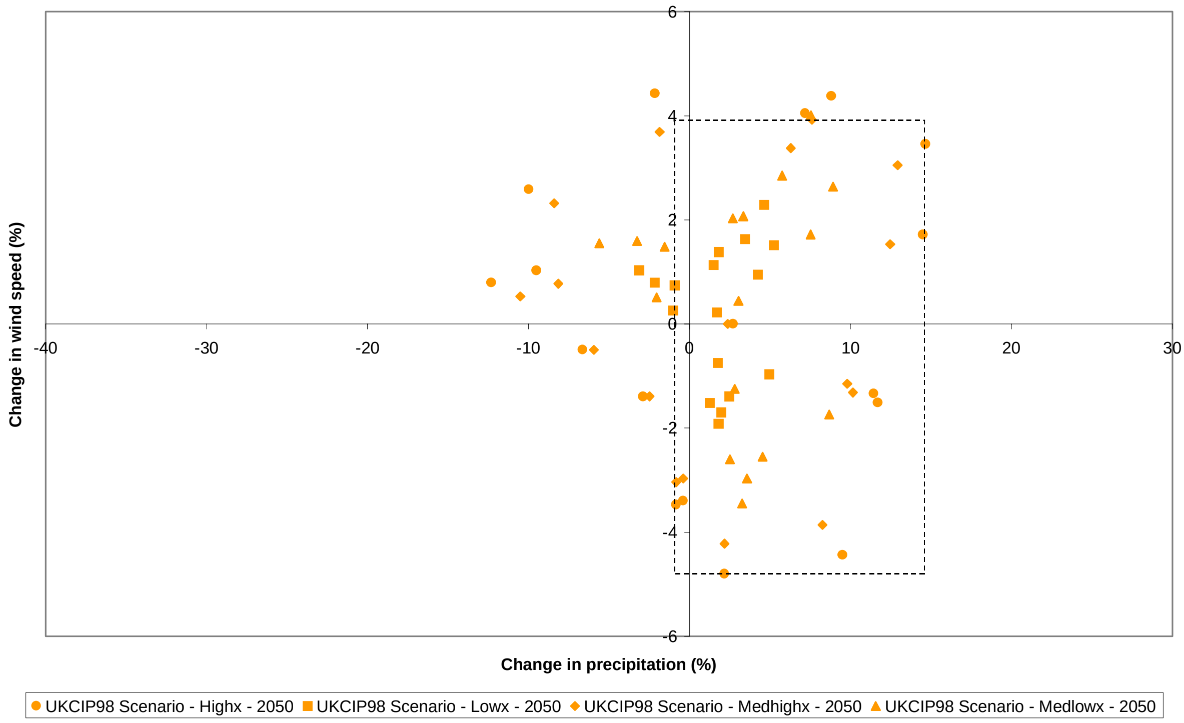



***Figure a**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

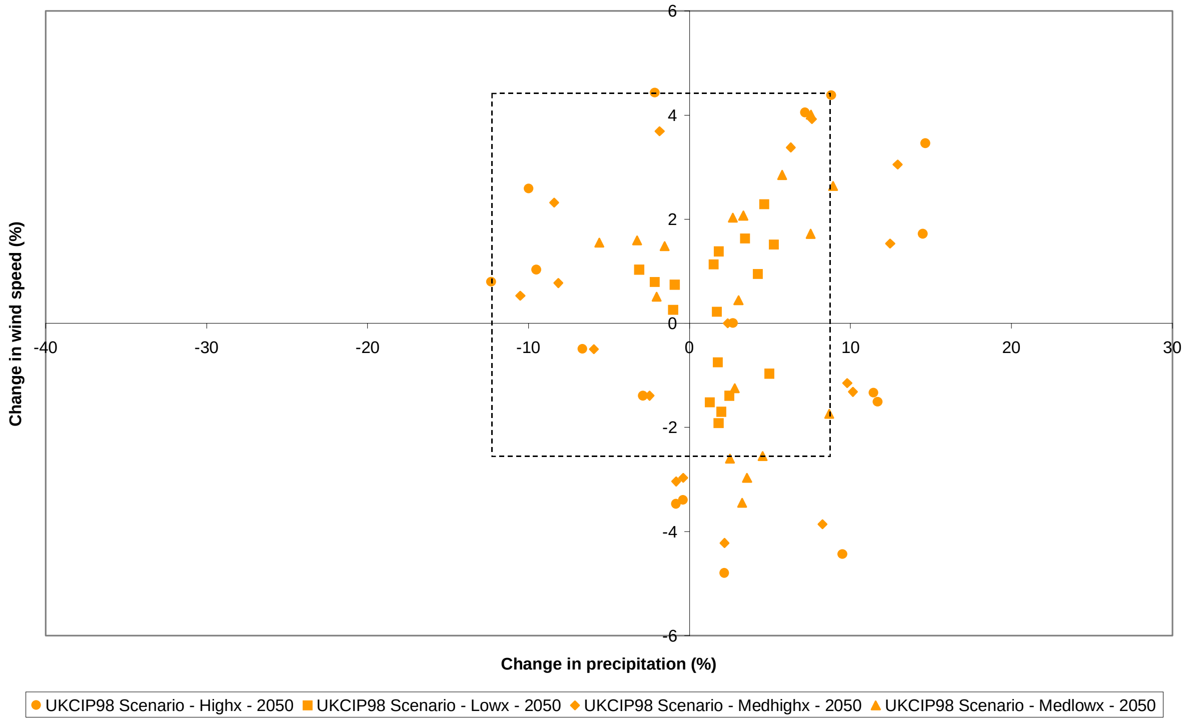



***Figure b**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

## Reservoir No.7 – North England

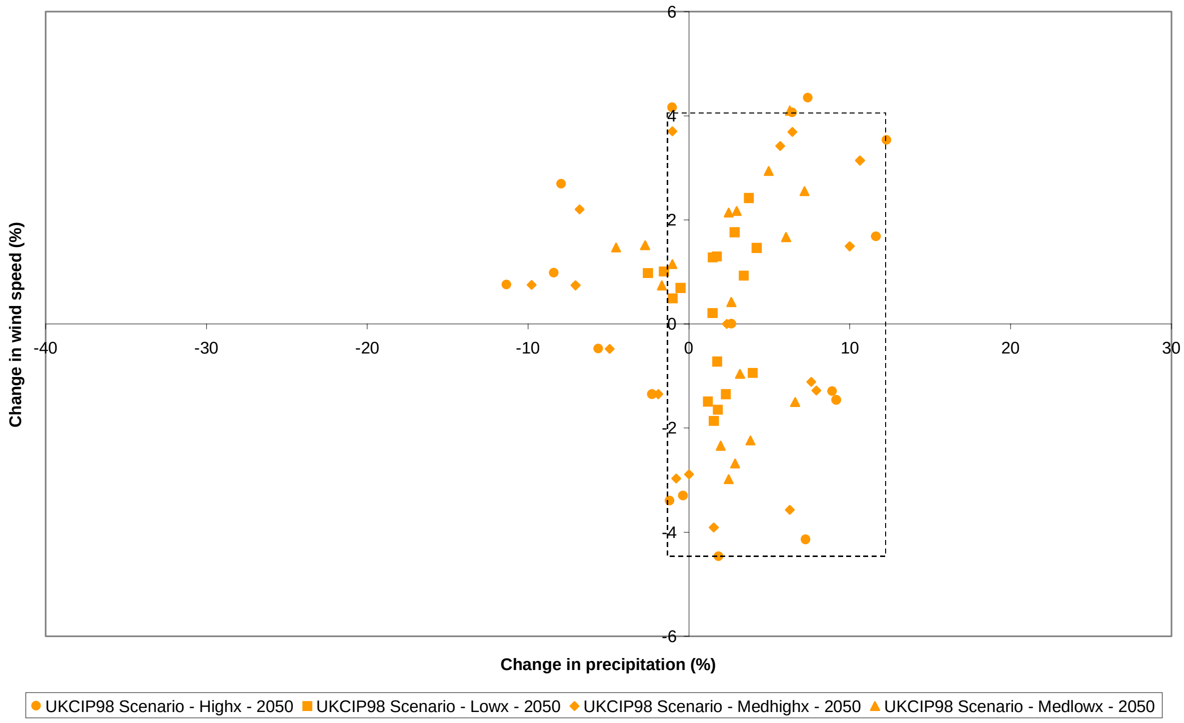



***Figure a***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

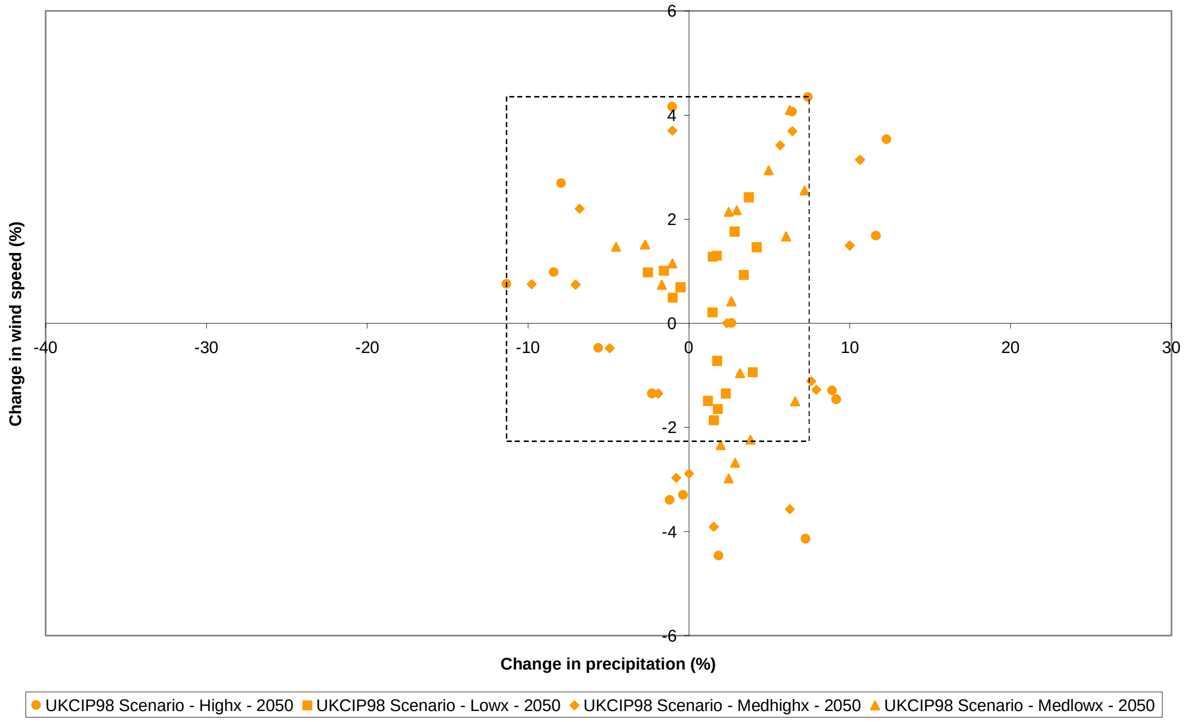



***Figure b***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

<u>Reservoir No.8 - Wales</u>

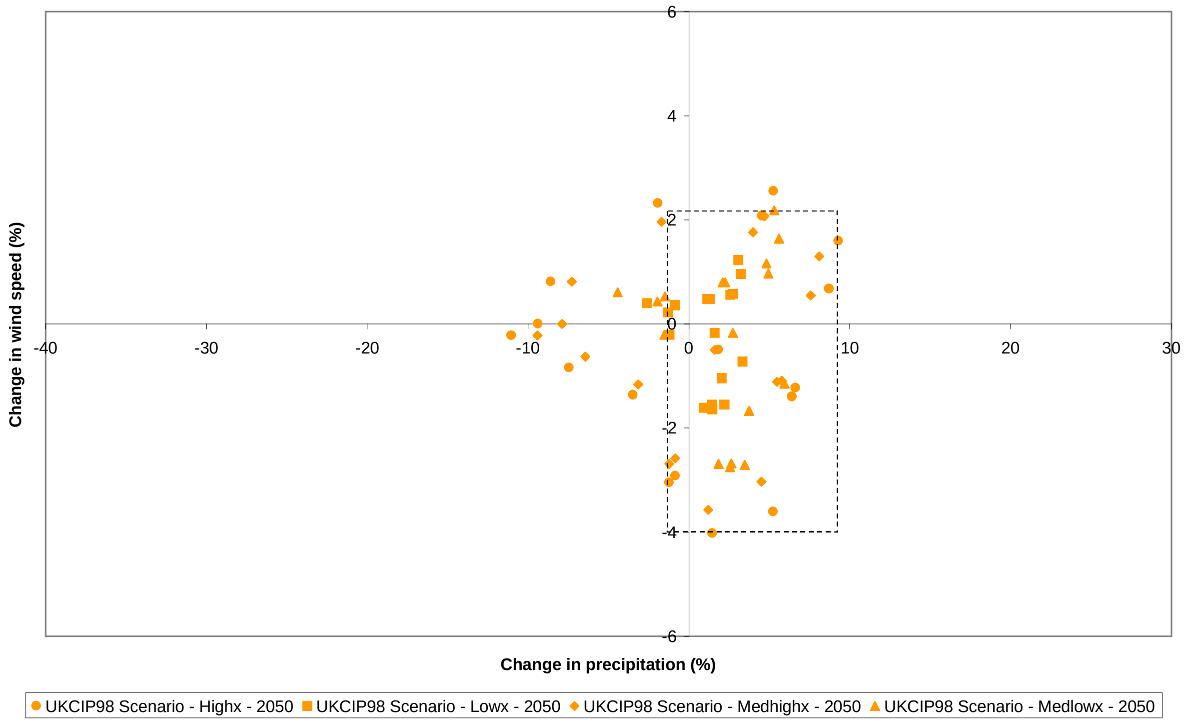



***Figure a***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

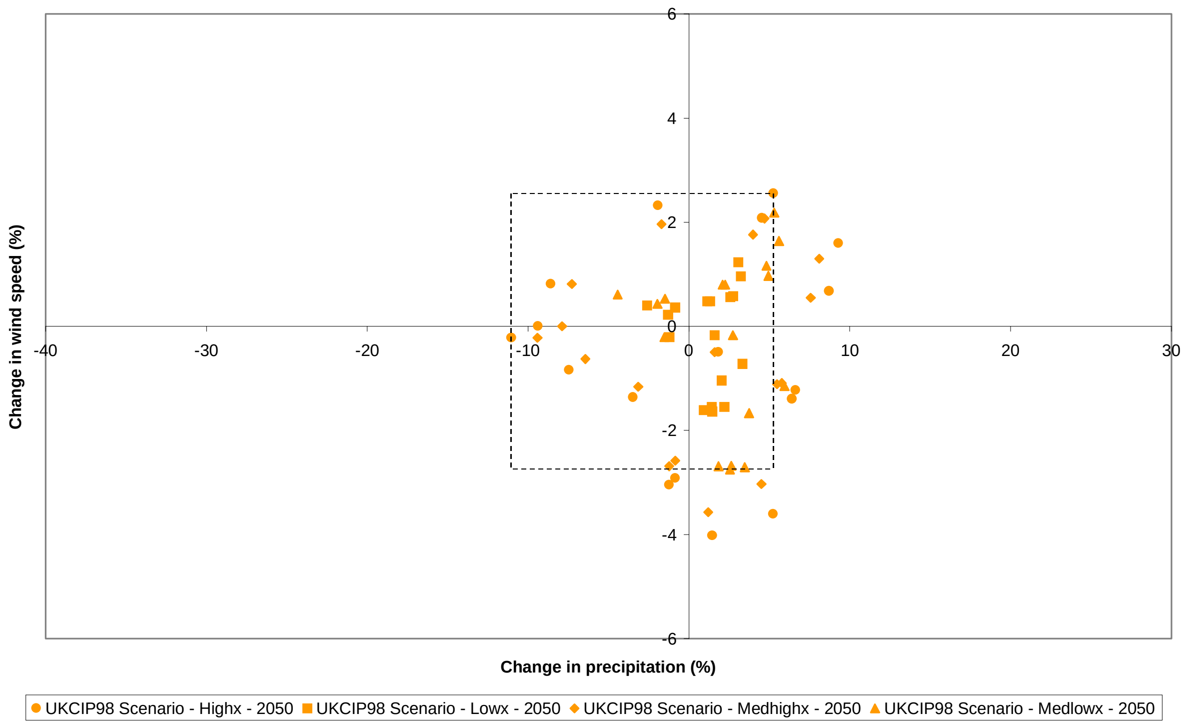



***Figure b***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

Reservoir No.9 - Wales

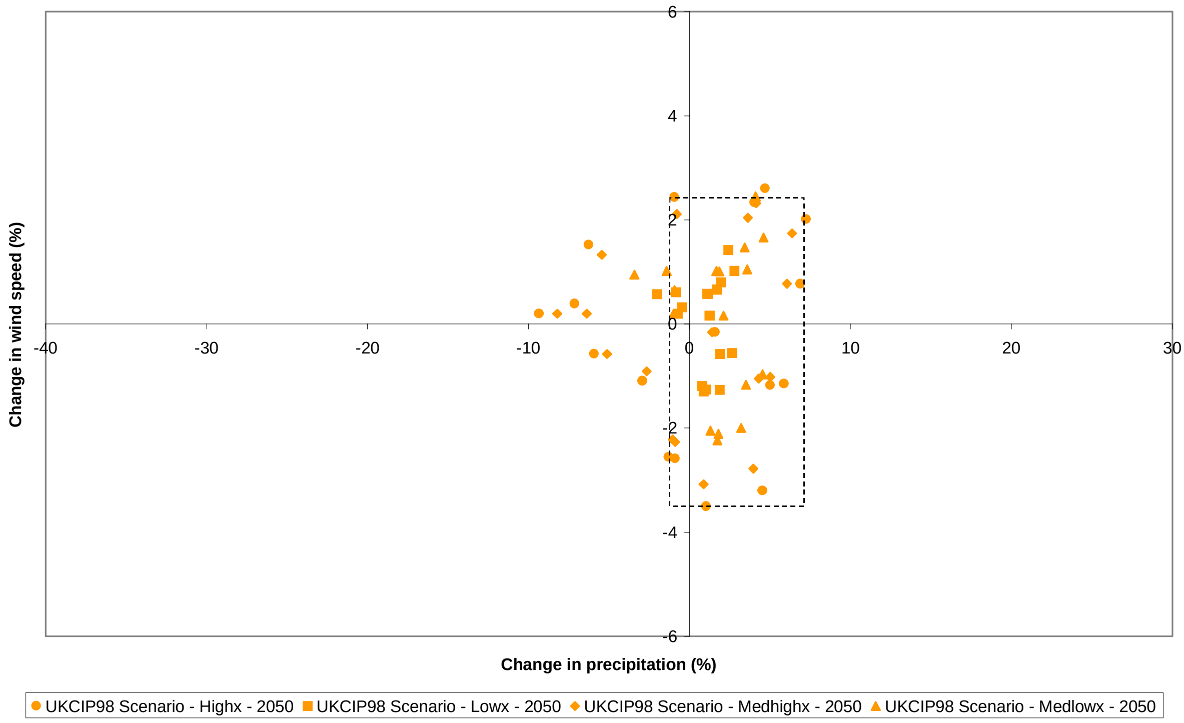



***Figure a****: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

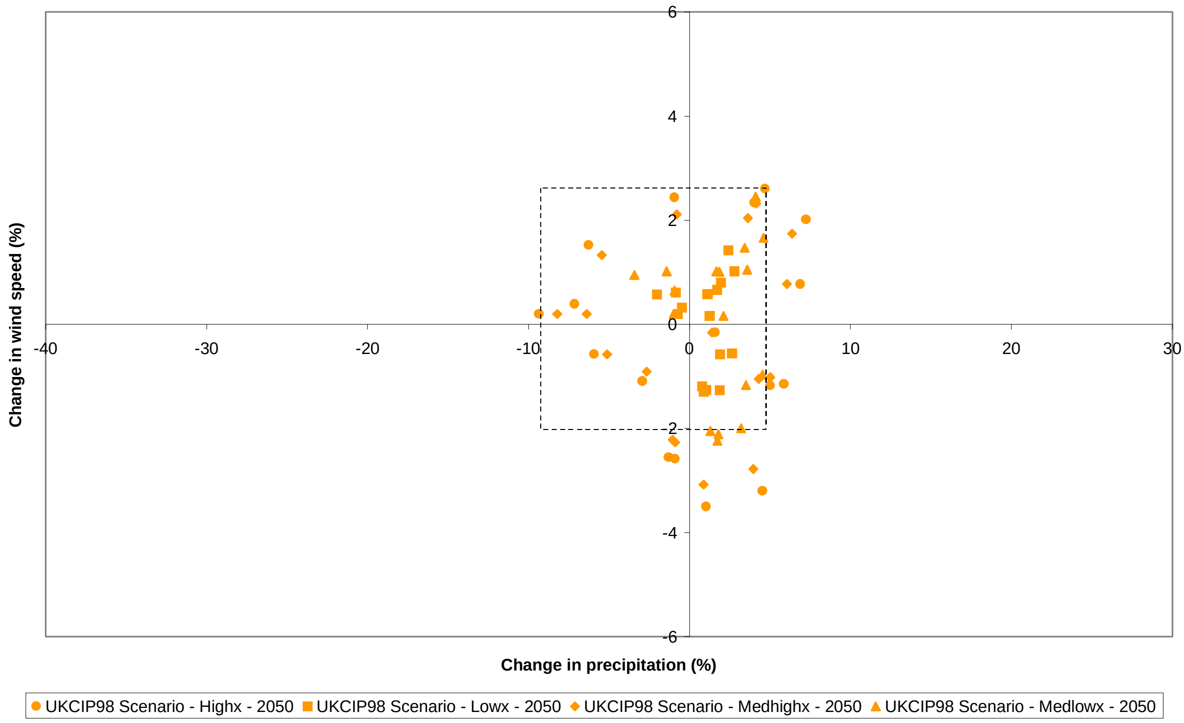



***Figure b****: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

Reservoir No.10 – S.W England

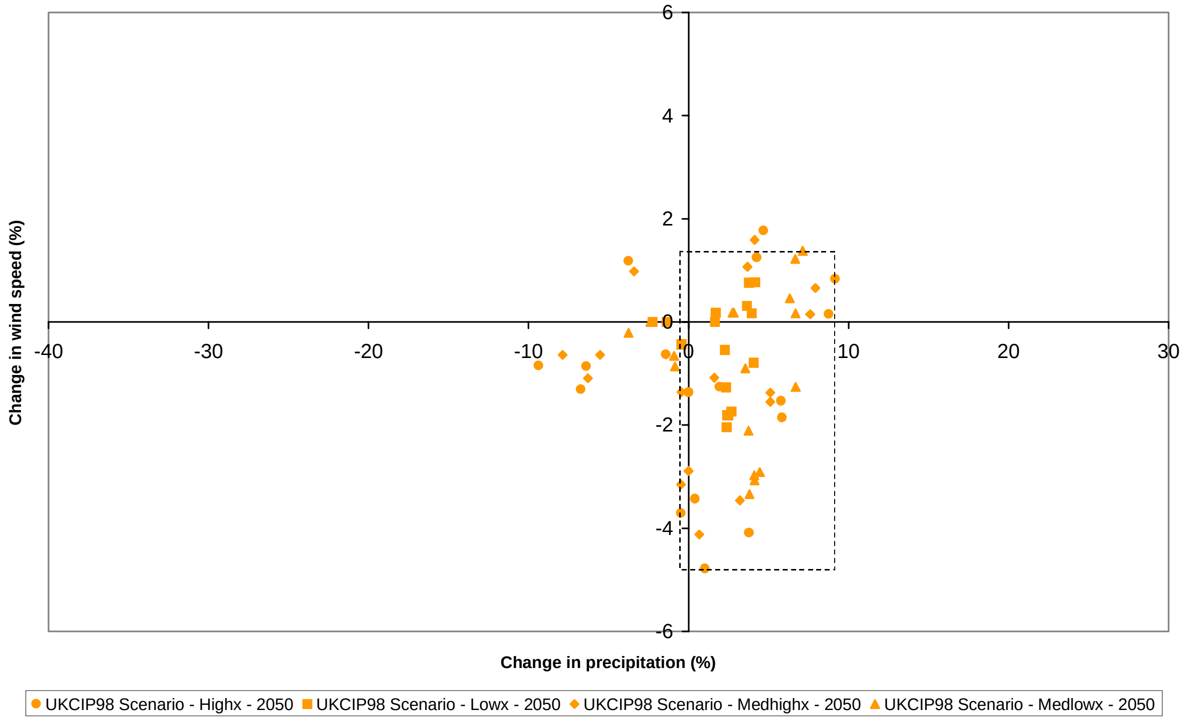



***Figure a**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

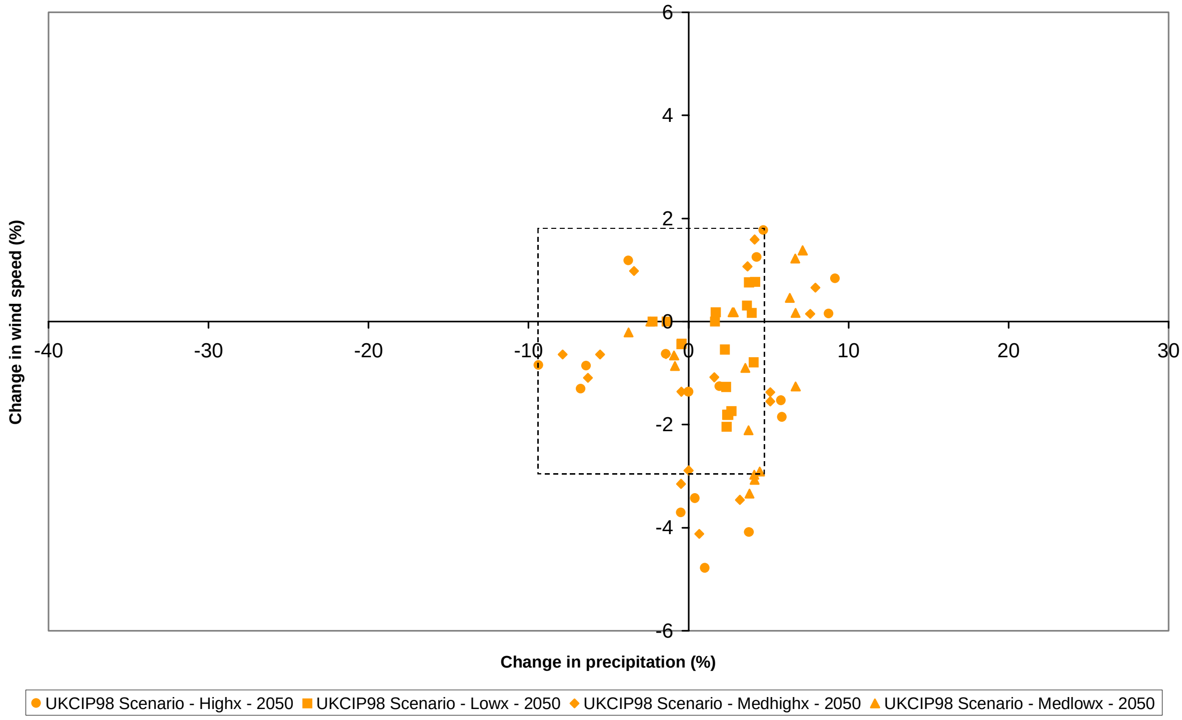



***Figure b**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

## Reservoir No.11 – S.W England

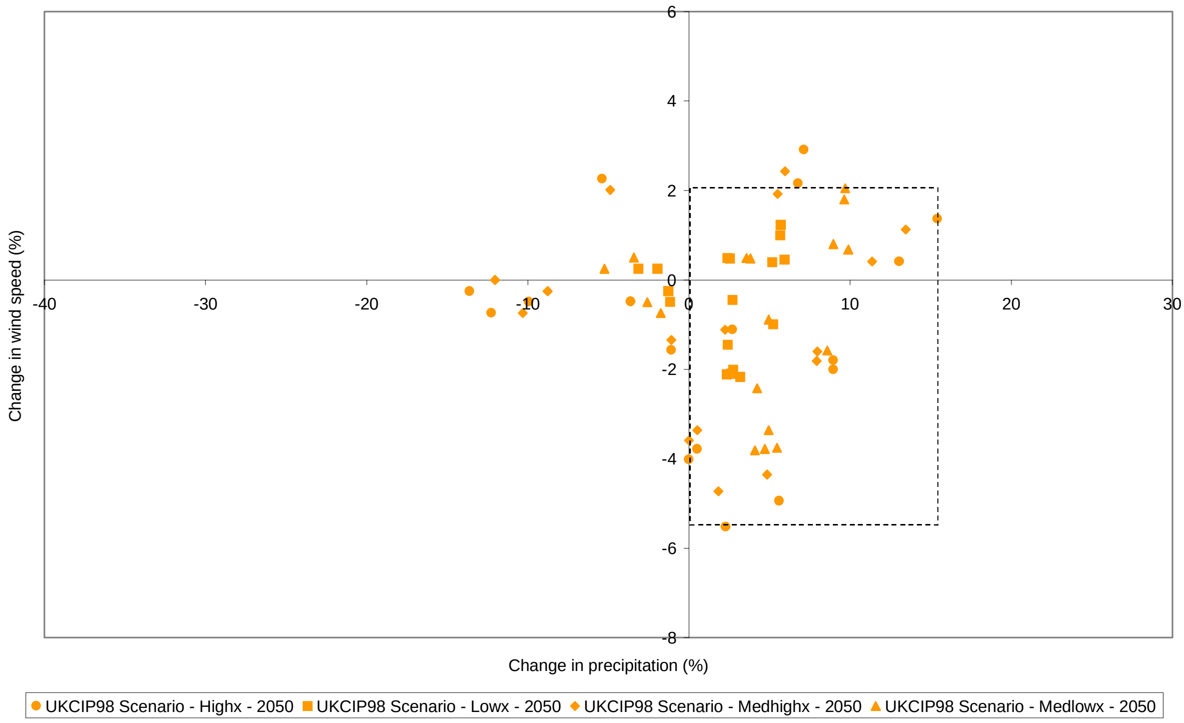



***Figure a****: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

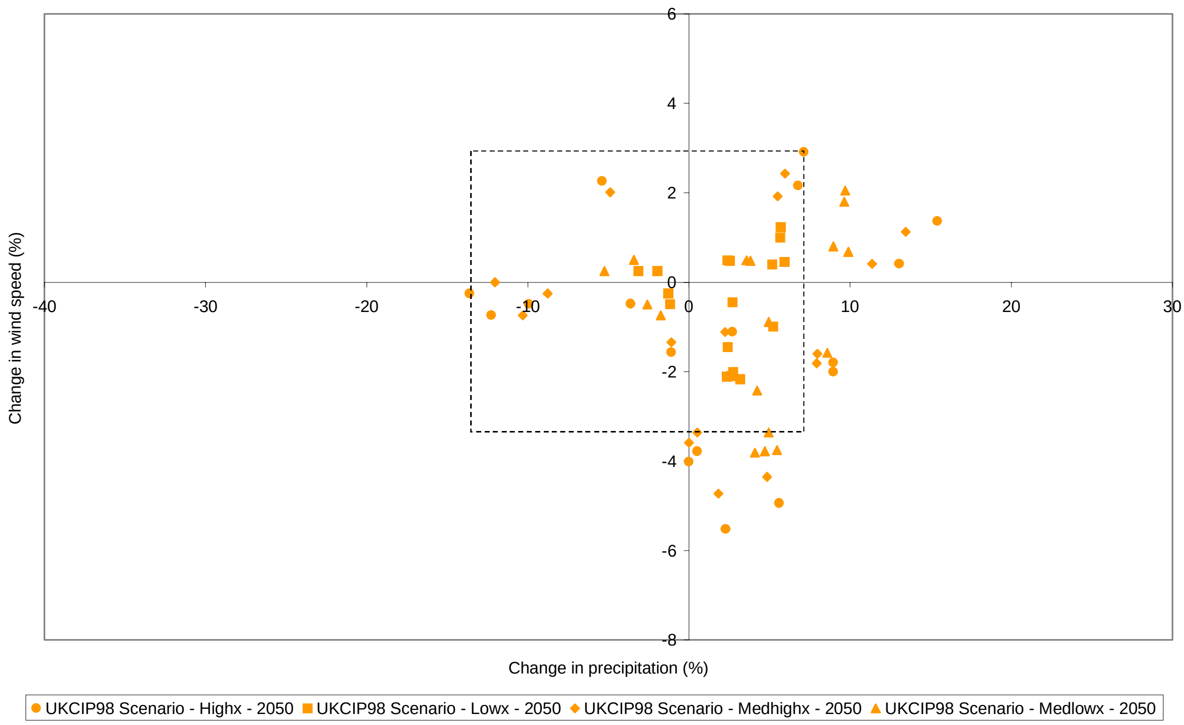



***Figure b****: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

## Reservoir No.12 – Central and S.E England

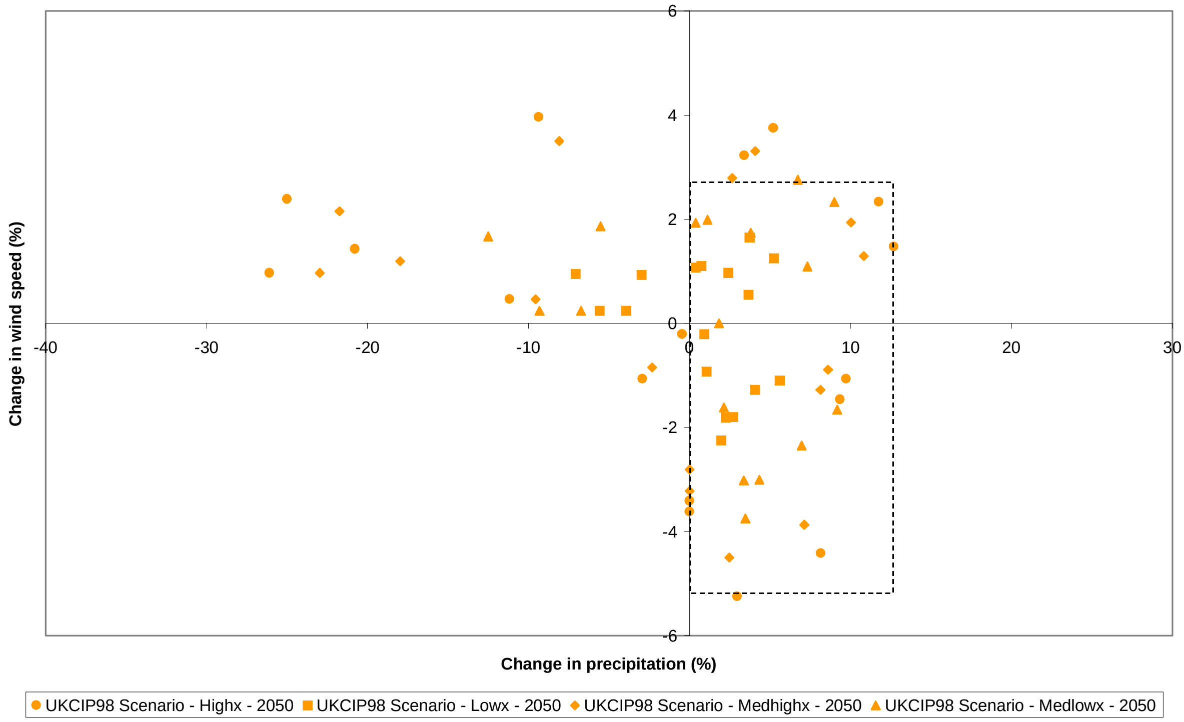



***Figure a***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

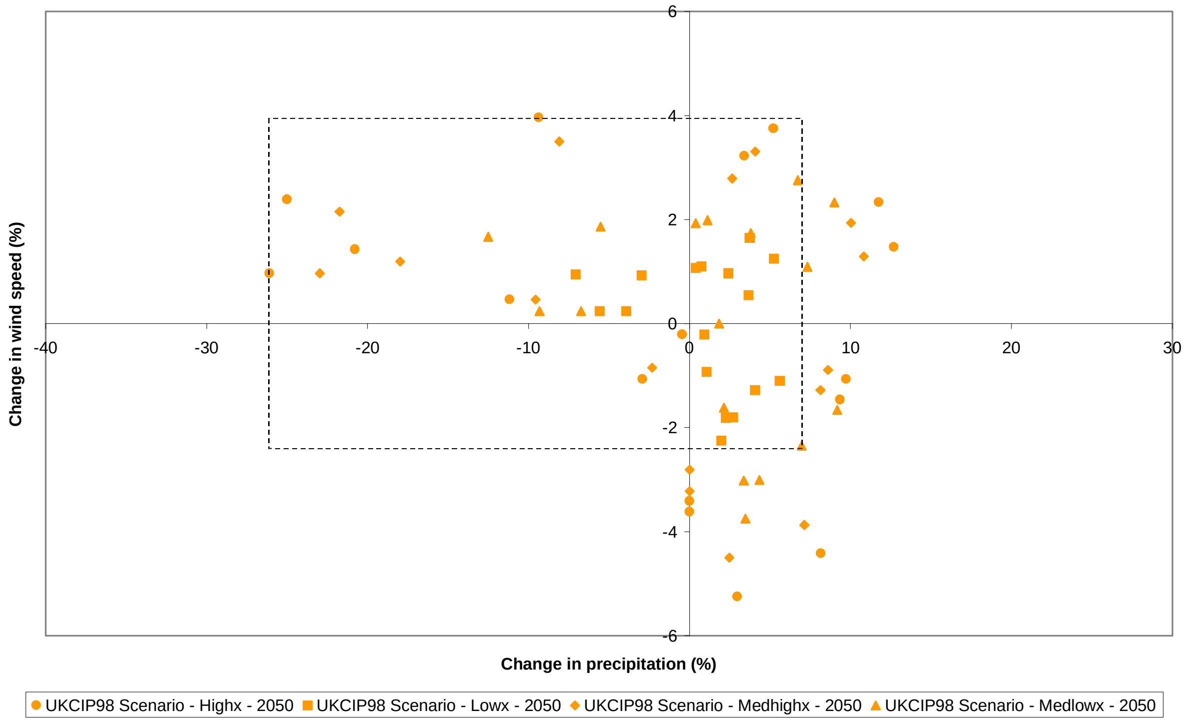



***Figure b***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

## Reservoir No.13 – Central and S.E England

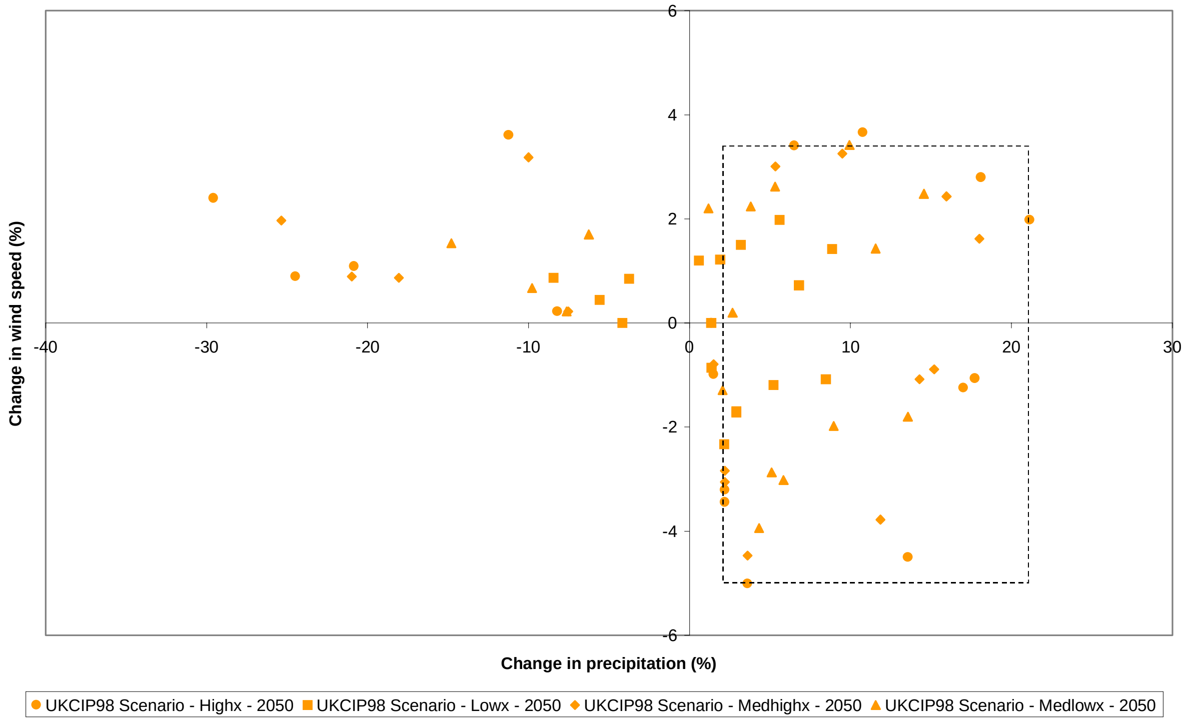



***Figure a***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

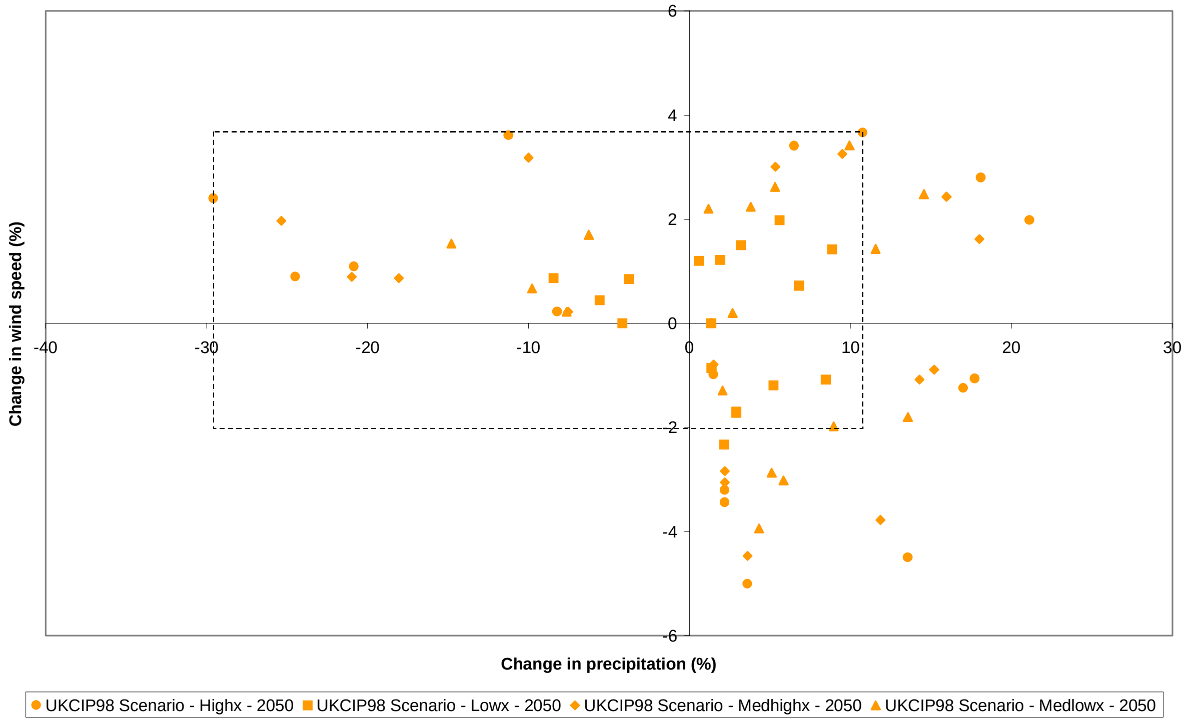



***Figure b***: *Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

## Reservoir No.14 – Central and S.E England

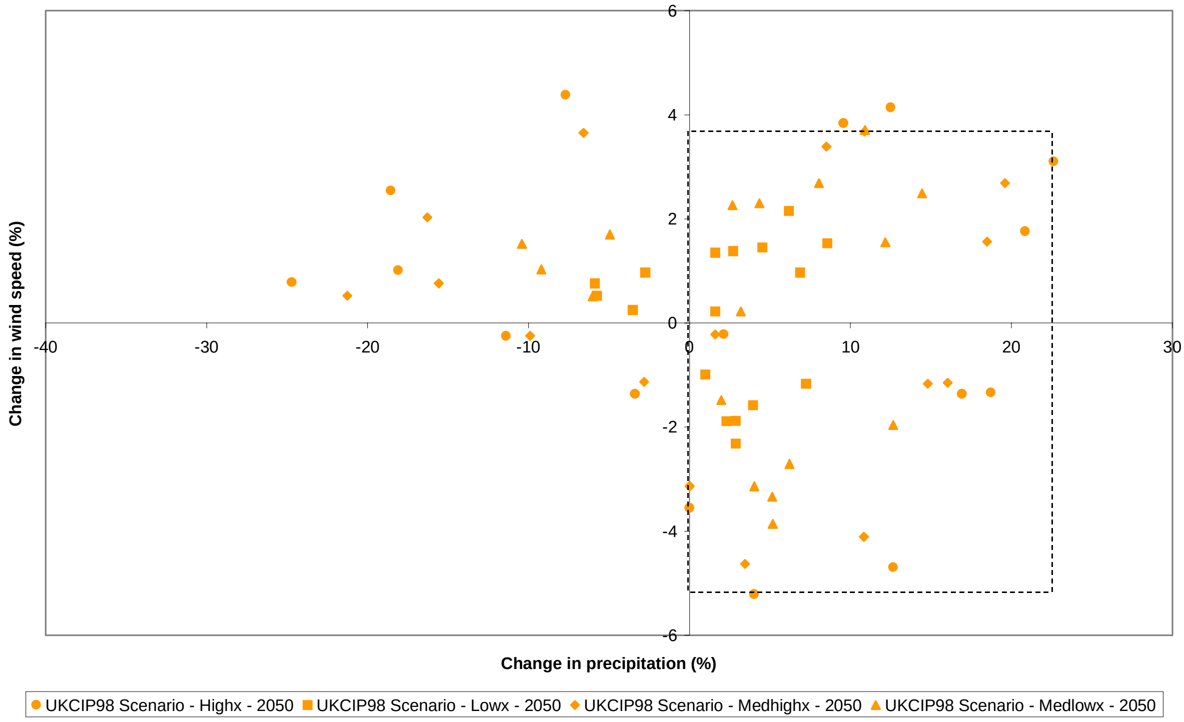



***Figure a**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the winter*

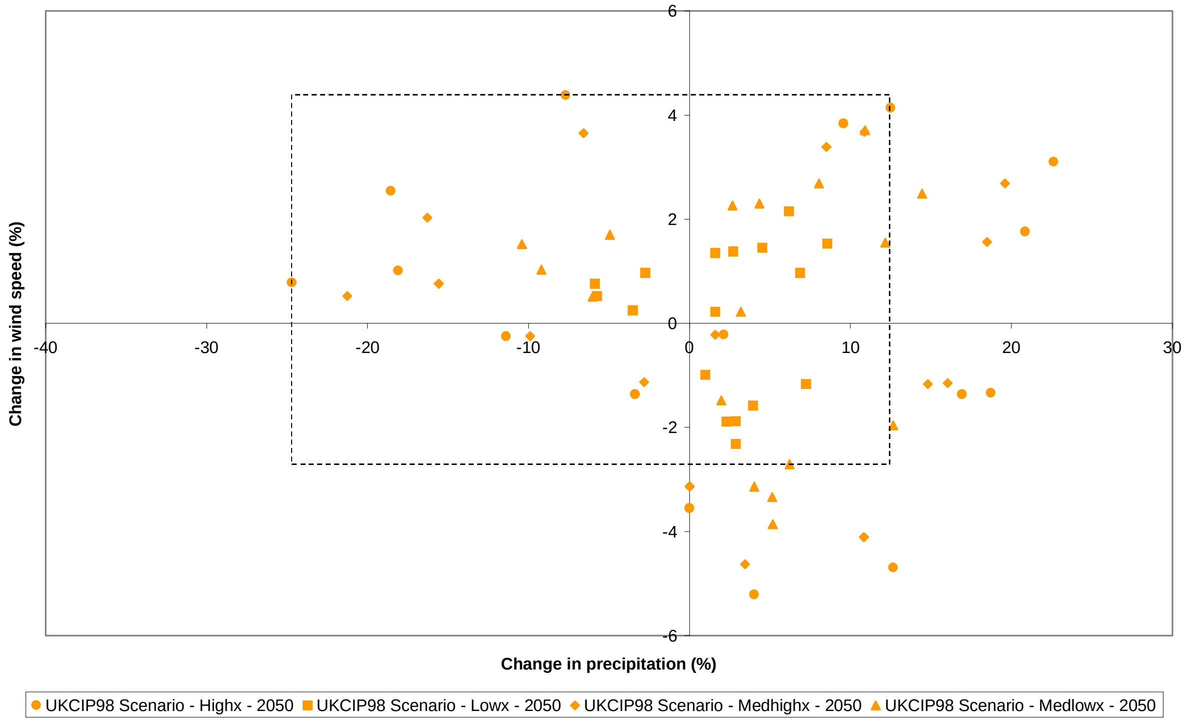



***Figure b**: Changes in rainfall against changes in wind speed for all scenarios – Range of scenarios for the summer*

# Appendix F

## Site Specific Climate Change Sensitivity

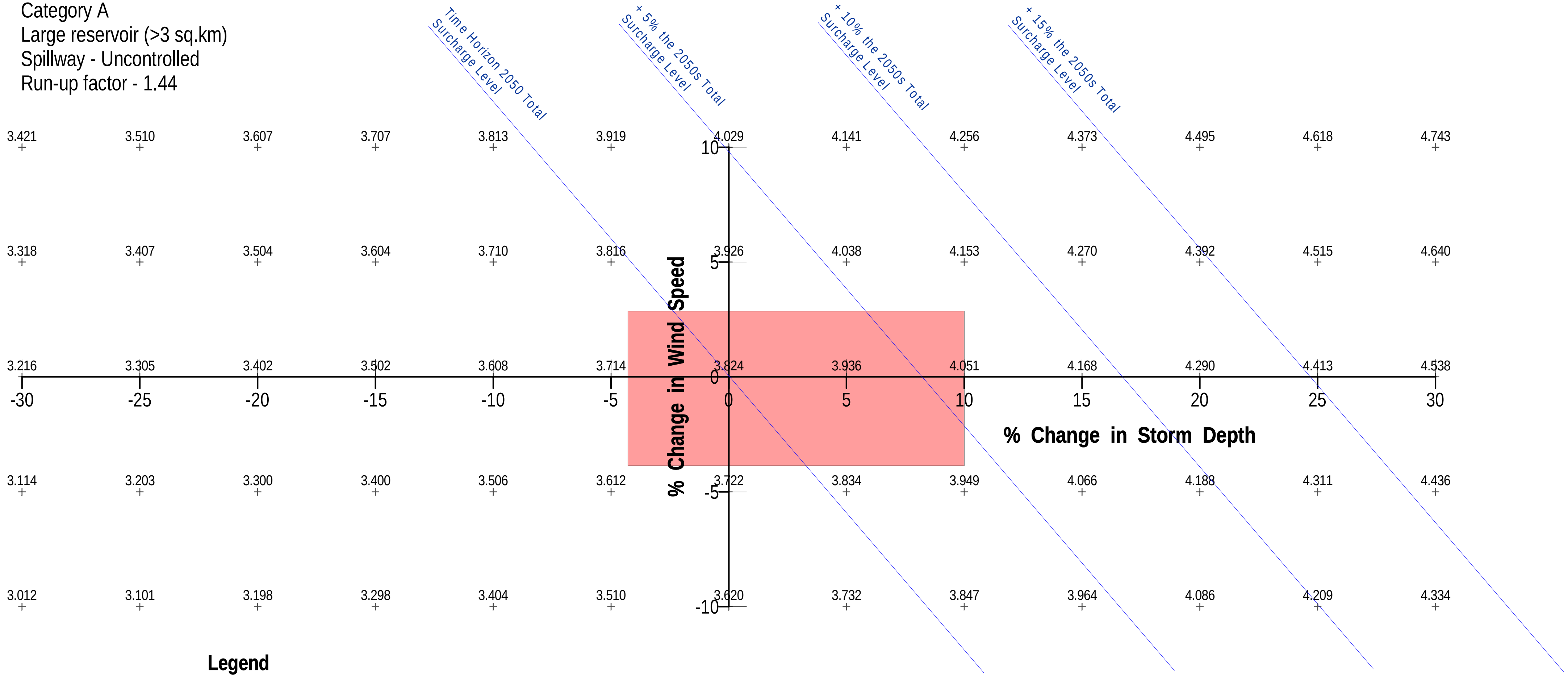
## Appendix F - Site Specific Climate Change Sensitivity

The following tables (28 No.) present sensitivity plots for winter and summer design storms at each representative reservoir site.

These tables are the principal output of the study from which conclusions have been drawn and which should form the basis of interpreting climate change impacts on any reservoir.

# Reservoir No. 1 - Winter PMF

Scotland
Category A
Large reservoir (>3 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.44




**Legend**

3.824 + Modelled total surcharge (m)

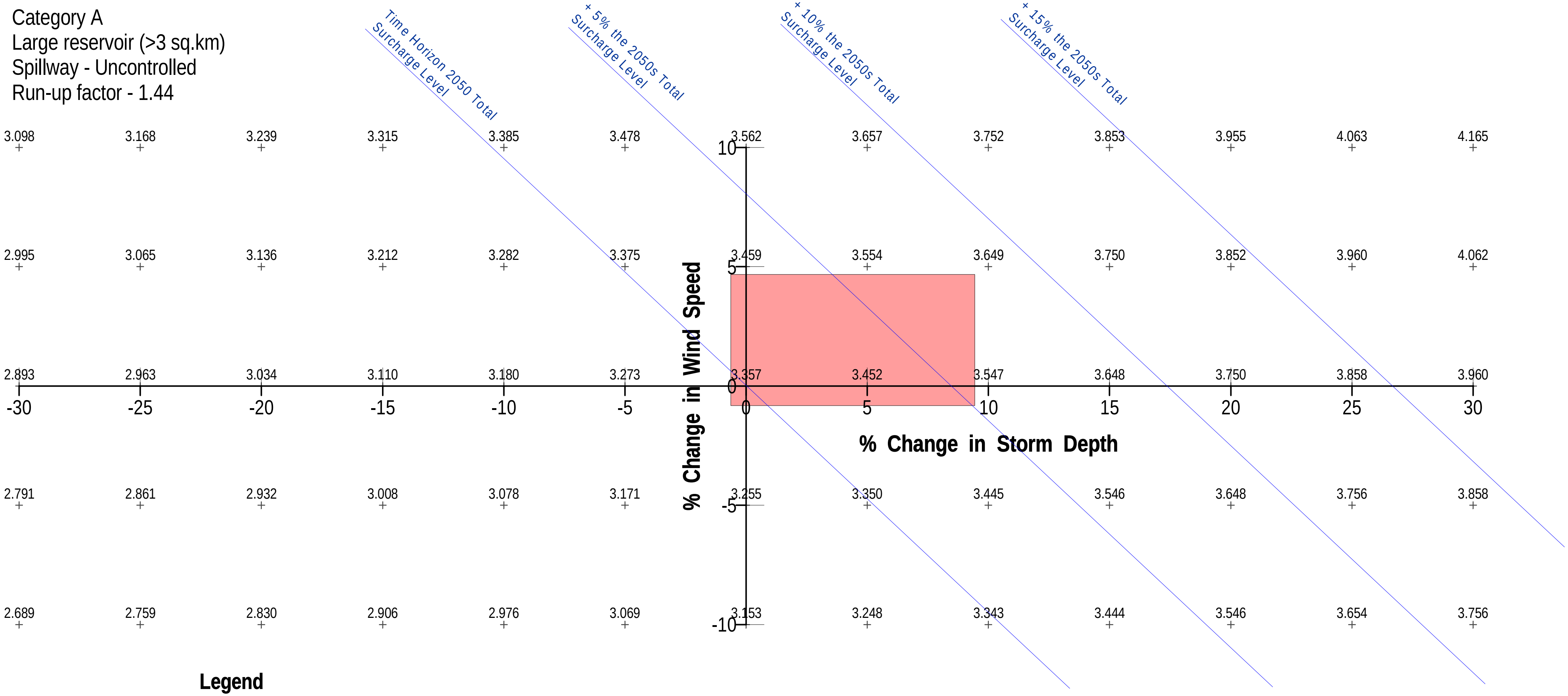
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentationd
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 1 - Summer PMF

Scotland
Category A
Large reservoir (>3 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.44




**Legend**

3.357 + Modelled total surcharge (m)

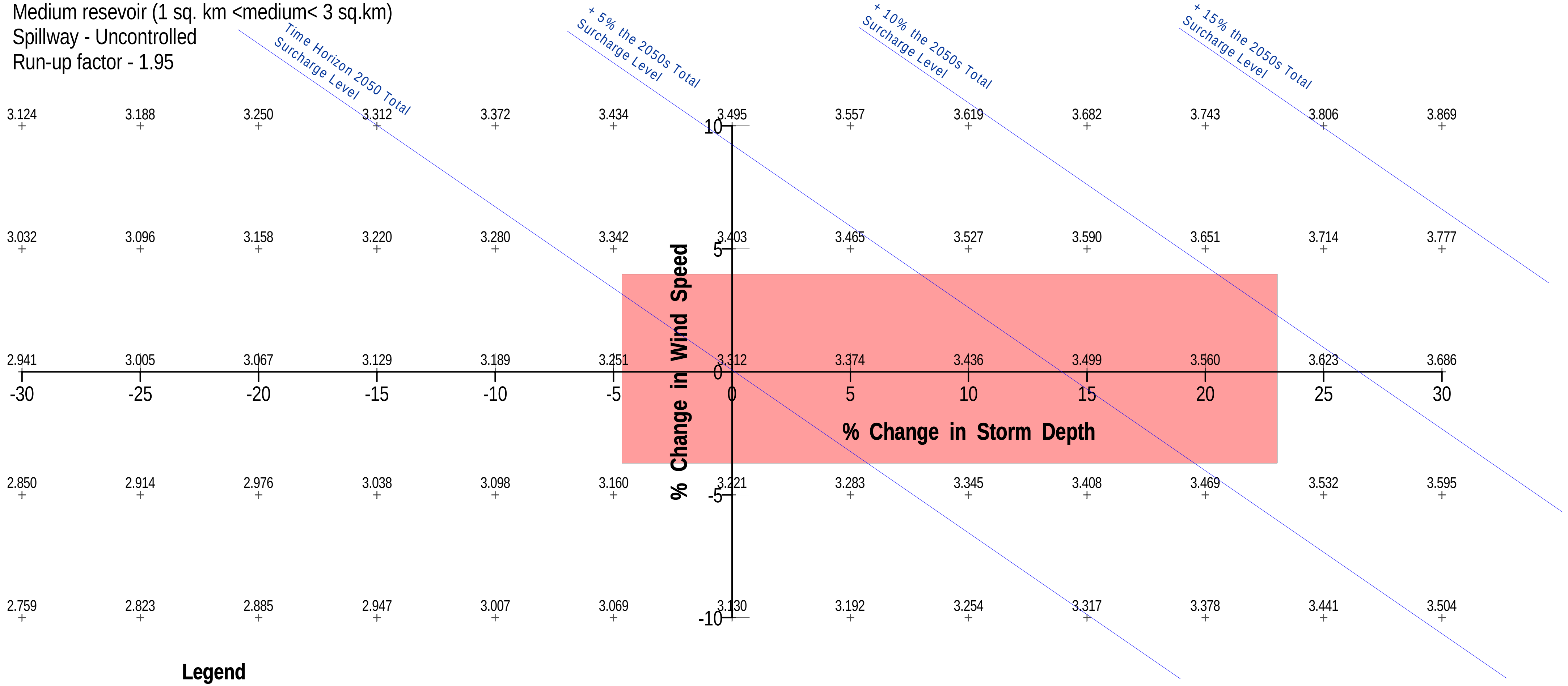
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 2 - Winter PMF

Scotland
Category A
Medium resevoir (1 sq. km <medium< 3 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.95




**Legend**

3.312 + Modelled total surcharge (m)

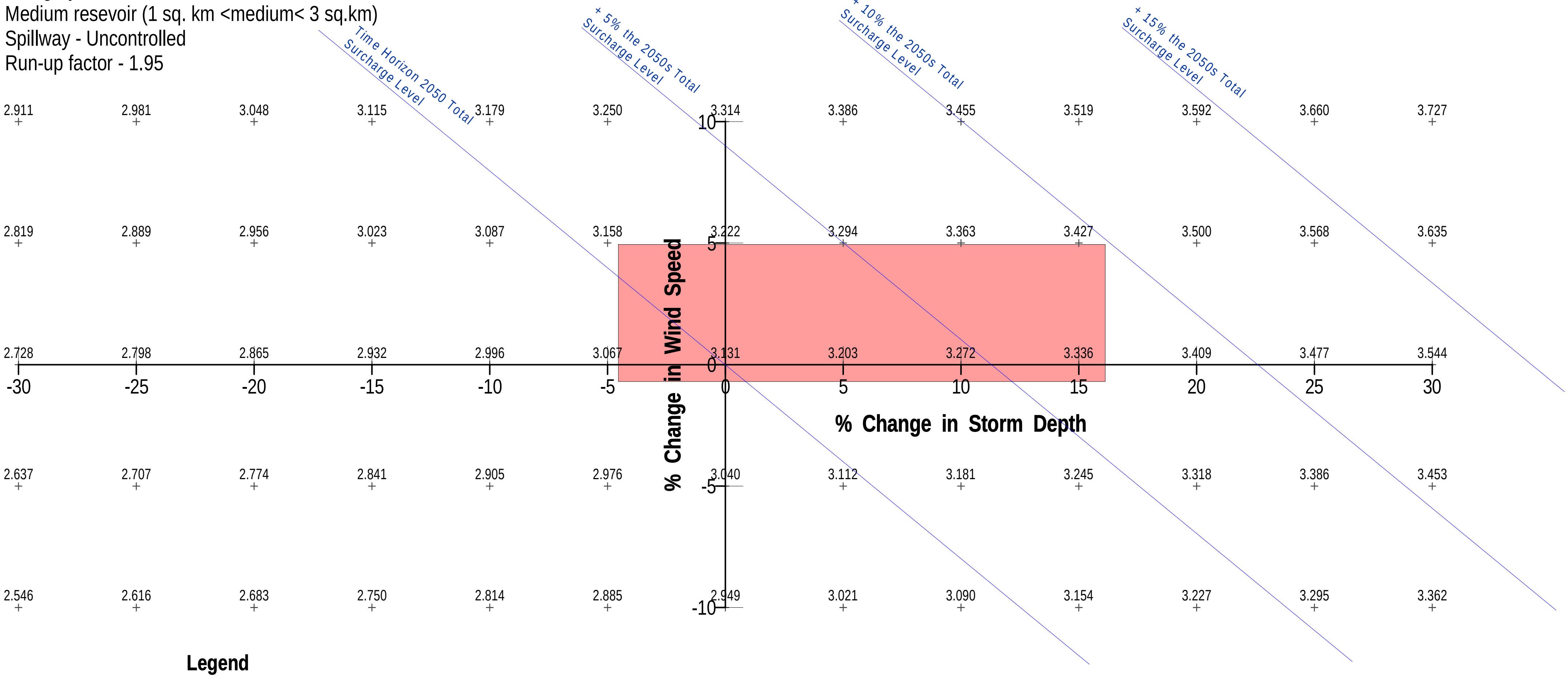
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 2 - Summer PMF

Scotland
Category A
Medium resevoir (1 sq. km <medium< 3 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.95




**Legend**

3.131 + Modelled total surcharge (m)

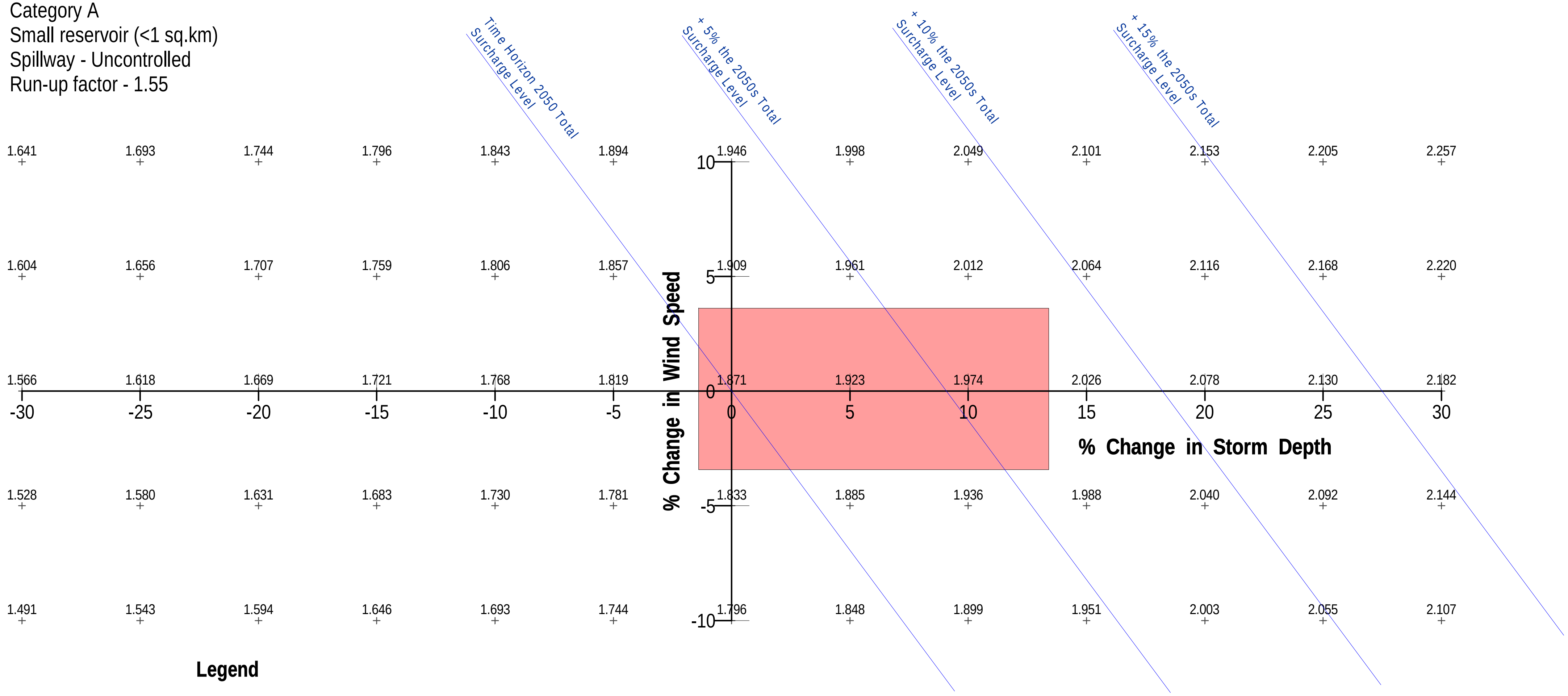
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 3 - Winter PMF

Scotland
Category A
Small reservoir (<1 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.55




## Legend

1.871 + Modelled total surcharge (m)

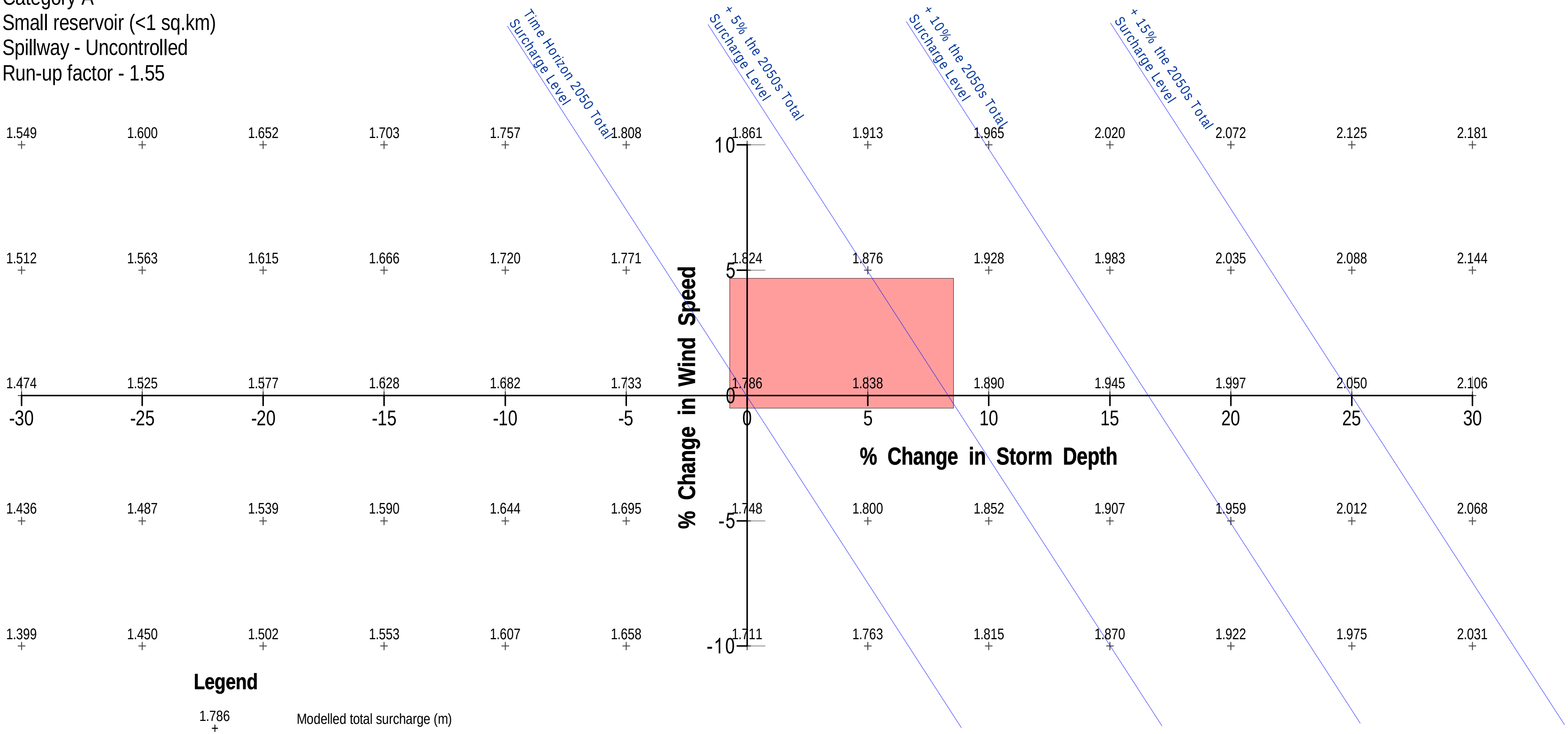
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 3 - Summer PMF

Scotland
Category A
Small reservoir (<1 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.55




**Legend**

1.786 + Modelled total surcharge (m)

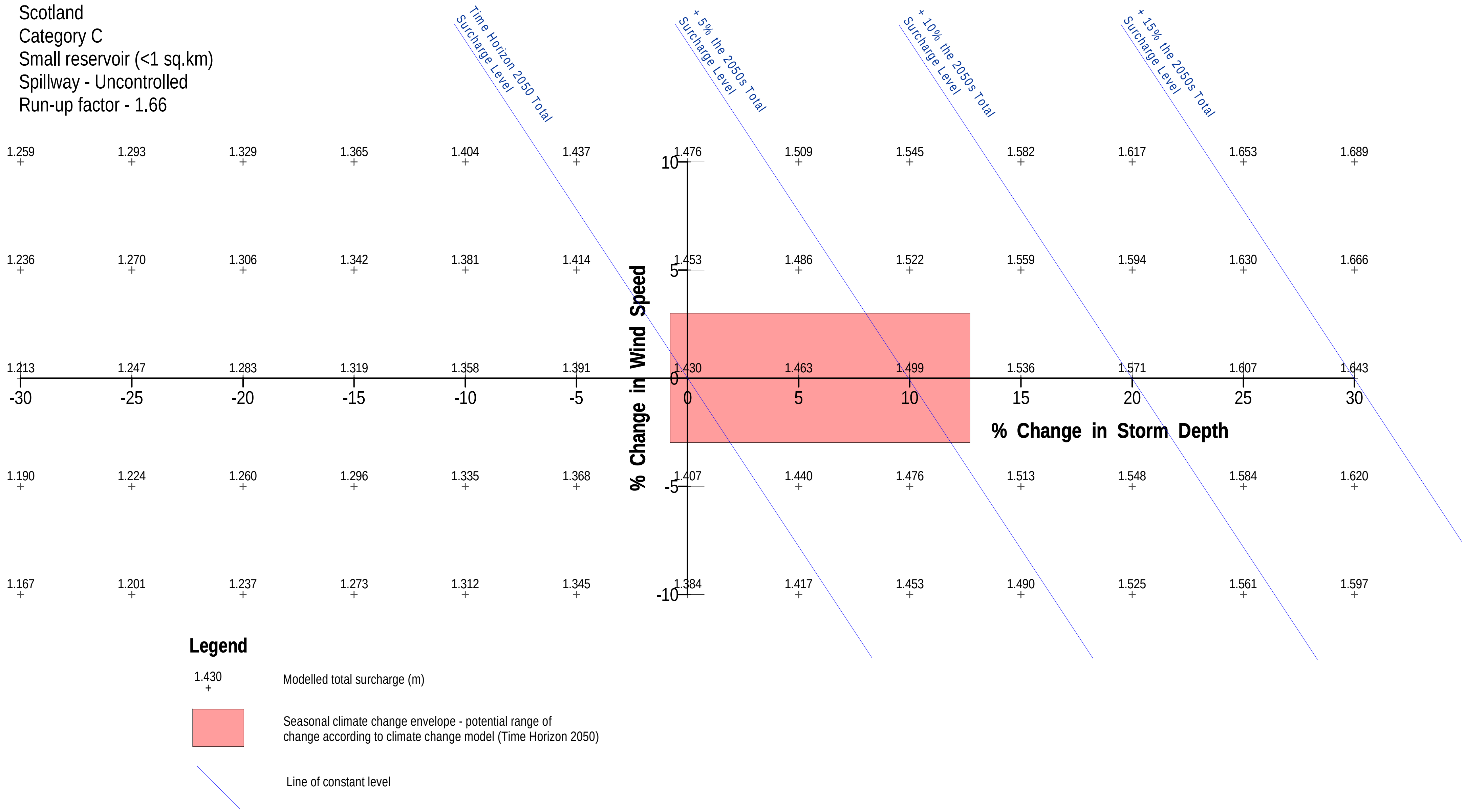
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 4 - Winter 1,000 Year

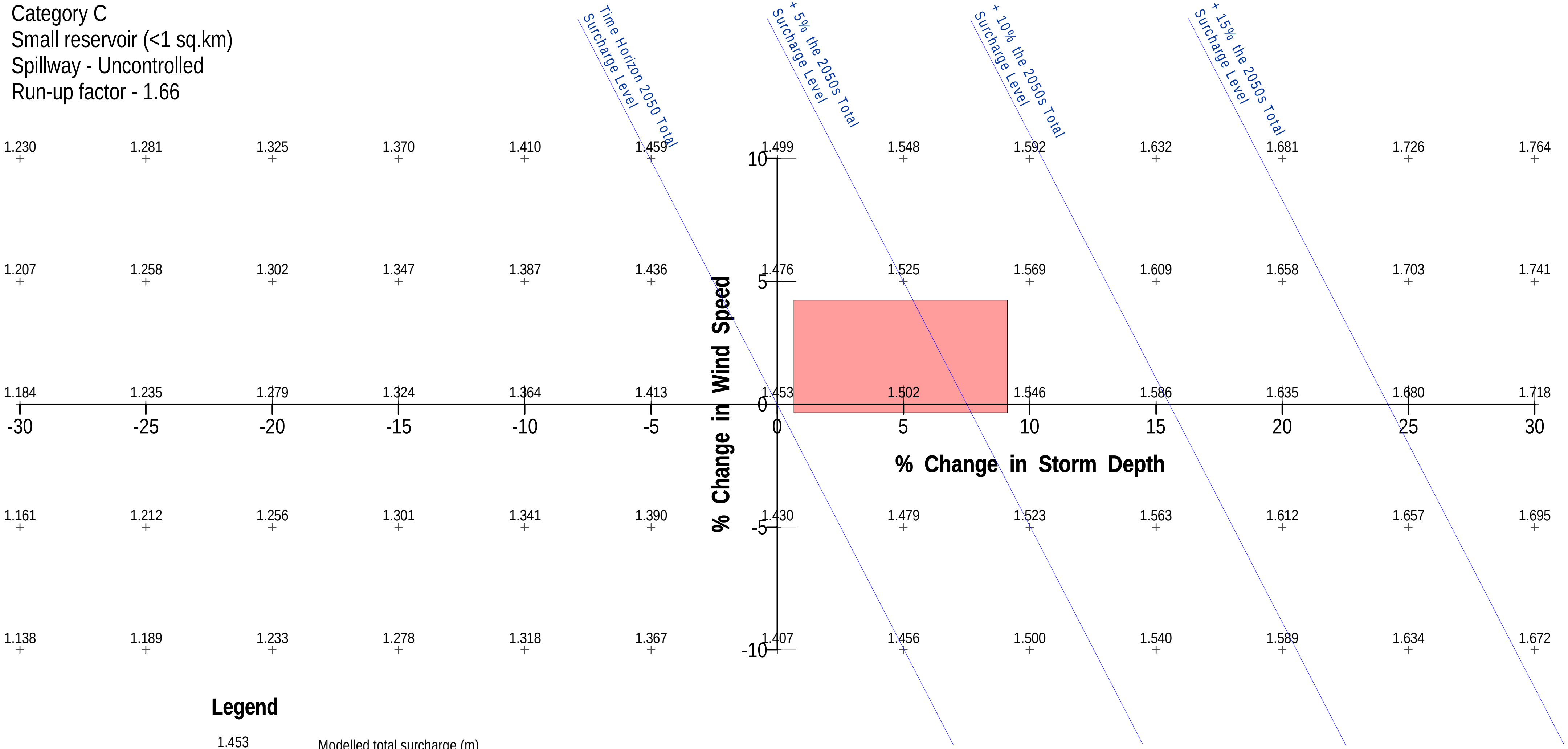
Scotland
Category C
Small reservoir (<1 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.66




**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 4 - Summer 1,000 Year

Scotland
Category C
Small reservoir (<1 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.66




## Legend

1.453 + Modelled total surcharge (m)

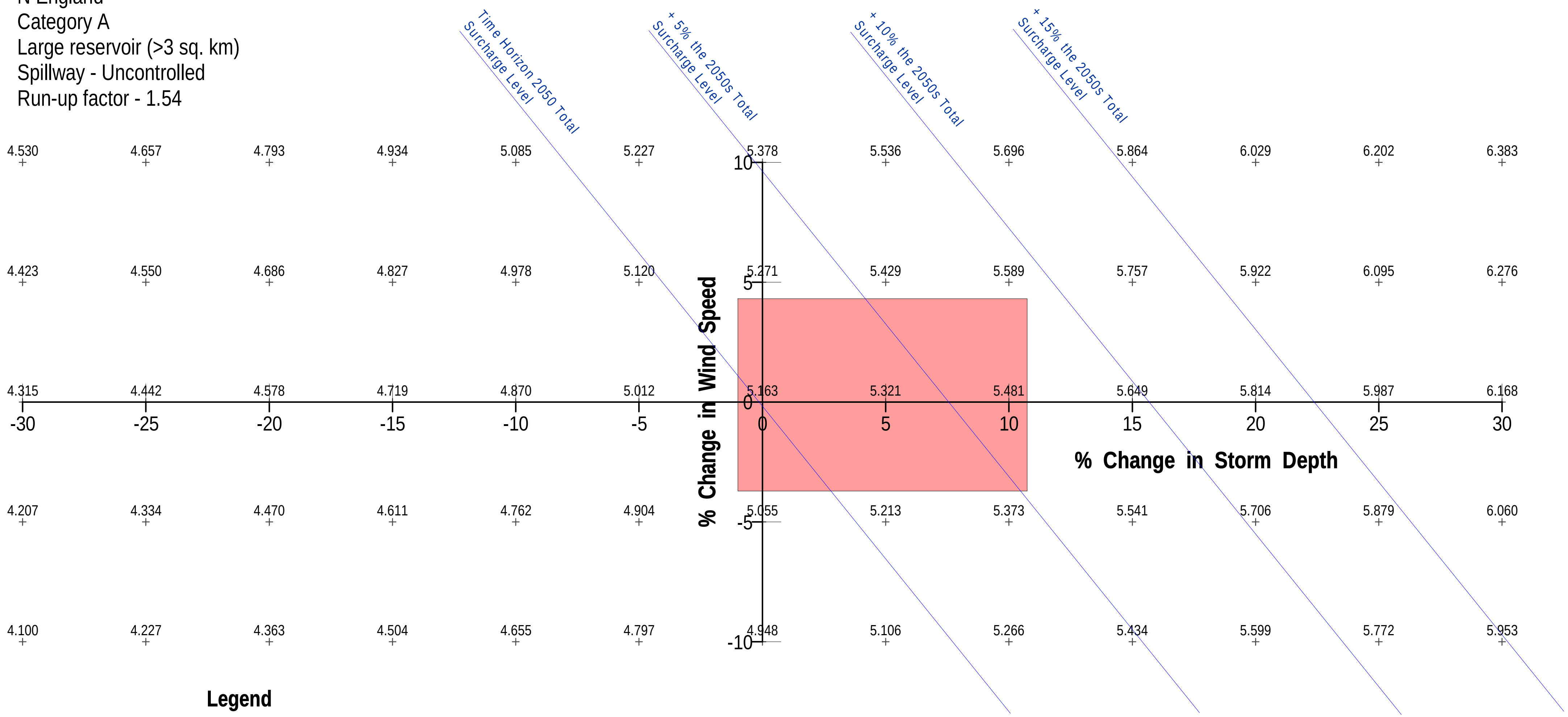
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 5 - Winter PMF

N England
Category A
Large reservoir (>3 sq. km)
Spillway - Uncontrolled
Run-up factor - 1.54




**Legend**

5.163 + Modelled total surcharge (m)

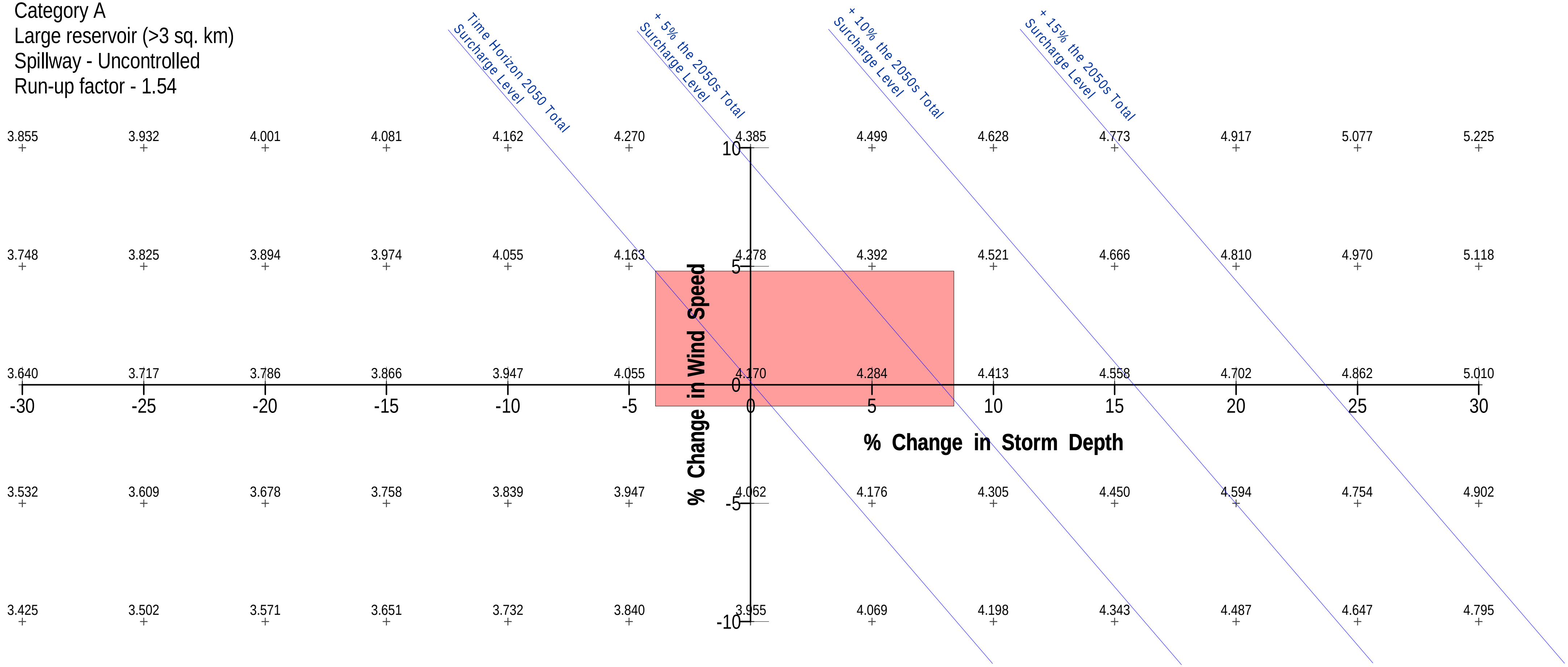
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 5 - Summer PMF

N England
Category A
Large reservoir (>3 sq. km)
Spillway - Uncontrolled
Run-up factor - 1.54




## Legend

4.170
+
Modelled total surcharge (m)

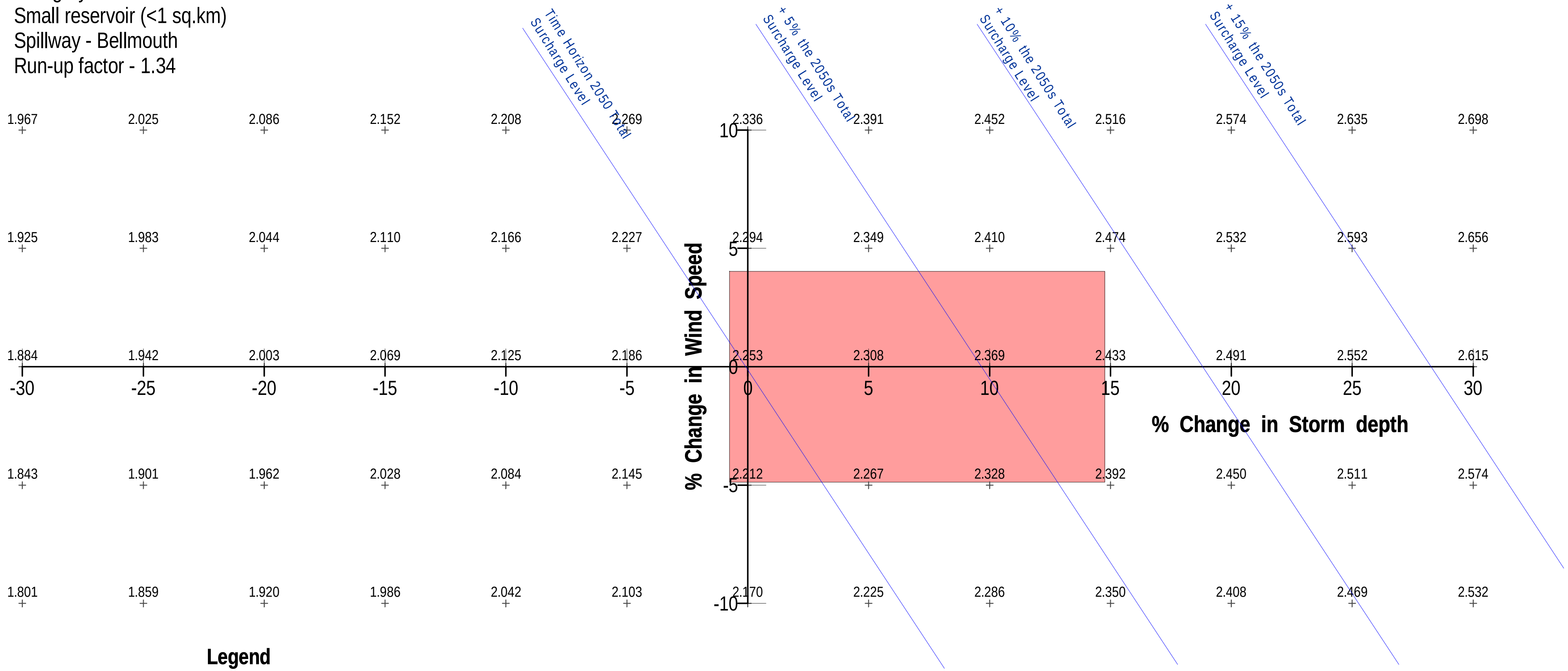
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 6 - Winter PMF

N England
Category A
Small reservoir (<1 sq.km)
Spillway - Bellmouth
Run-up factor - 1.34




### Legend

2.253 + Modelled total surcharge (m)

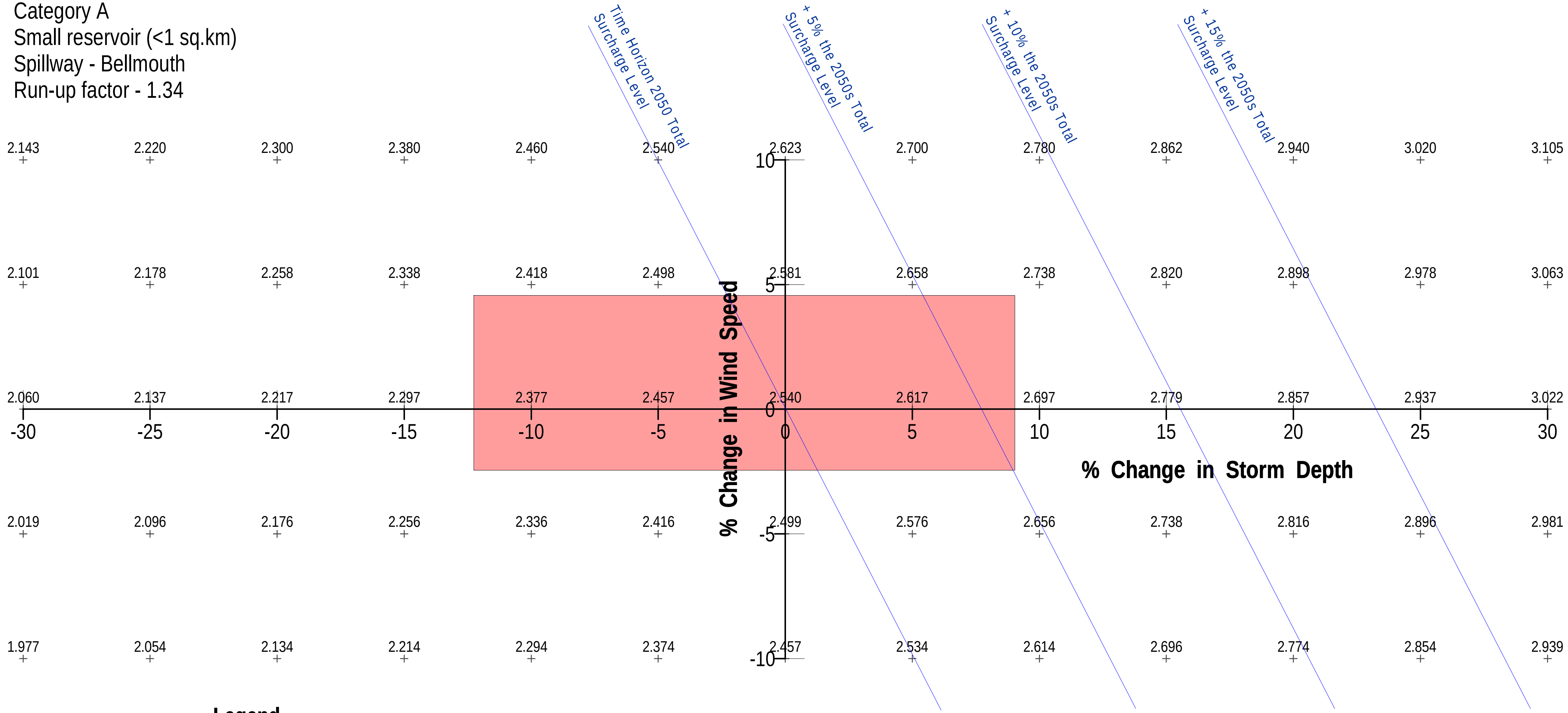
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 6 - Summer PMF

N England
Category A
Small reservoir (<1 sq.km)
Spillway - Bellmouth
Run-up factor - 1.34




### Legend

2.540 + — Modelled total surcharge (m)

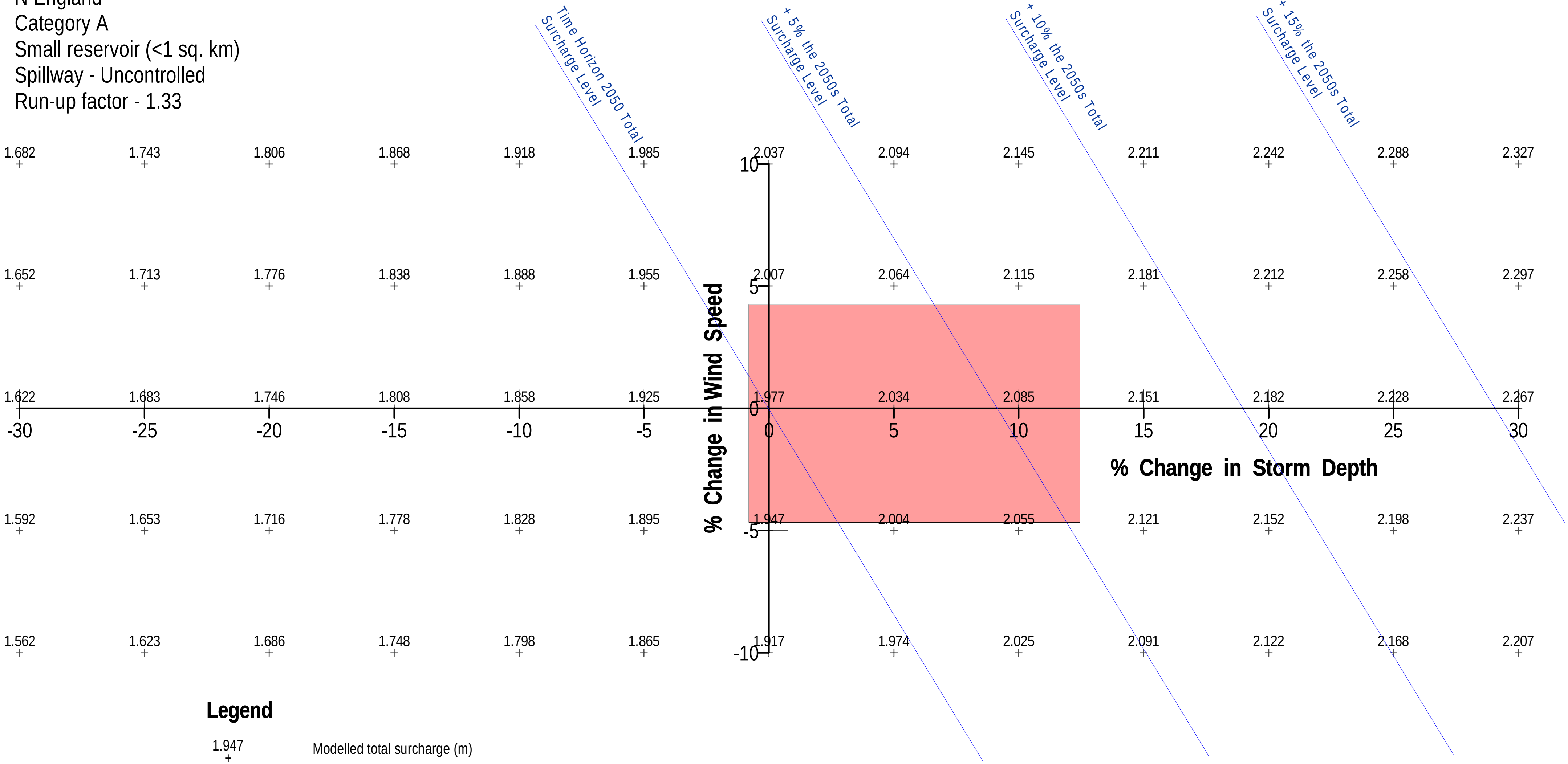
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 7 - Winter PMF

N England
Category A
Small reservoir (<1 sq. km)
Spillway - Uncontrolled
Run-up factor - 1.33




## Legend

1.947 + Modelled total surcharge (m)

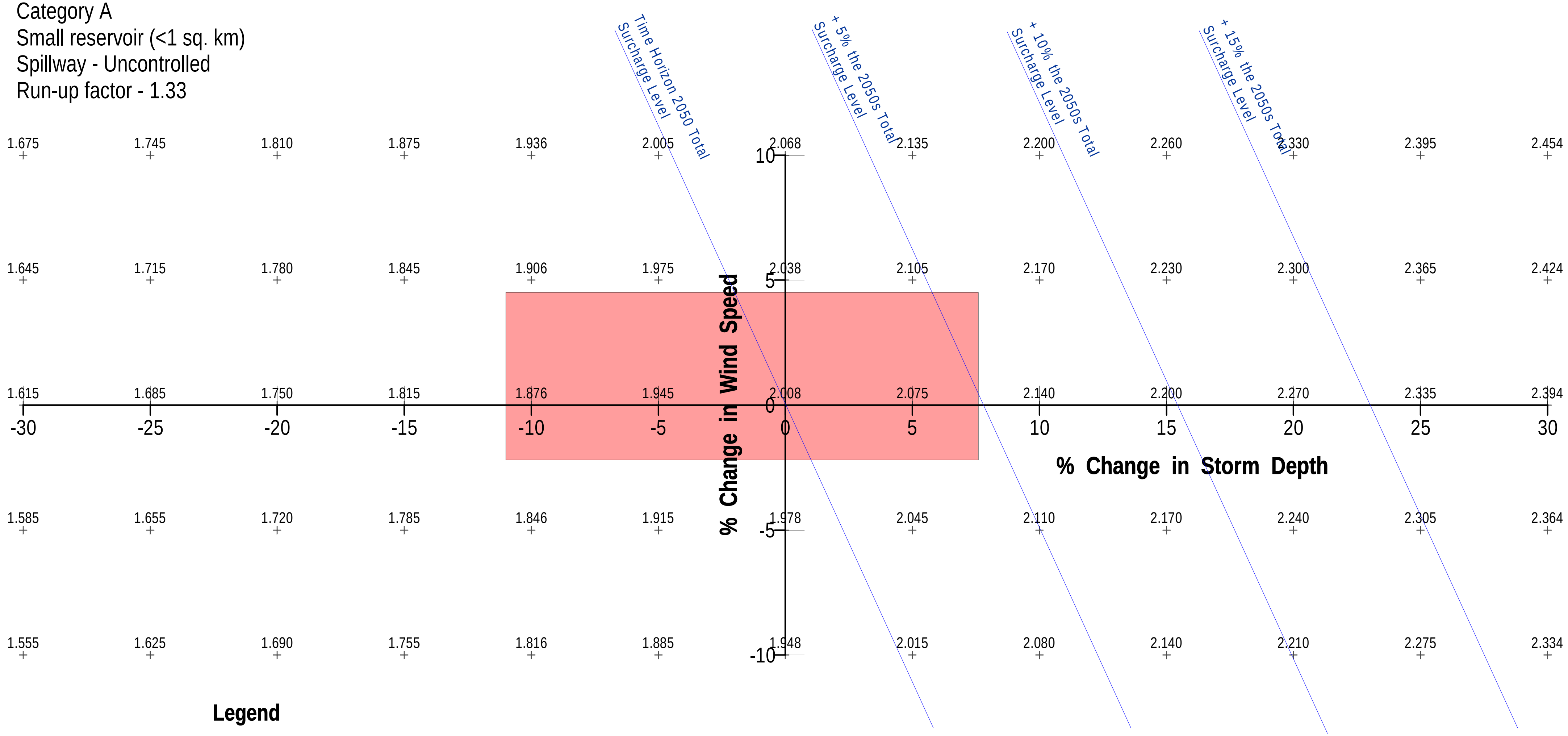
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 7 - Summer PMF

N England
Category A
Small reservoir (<1 sq. km)
Spillway - Uncontrolled
Run-up factor - 1.33




## Legend

2.008 + Modelled total surcharge (m)

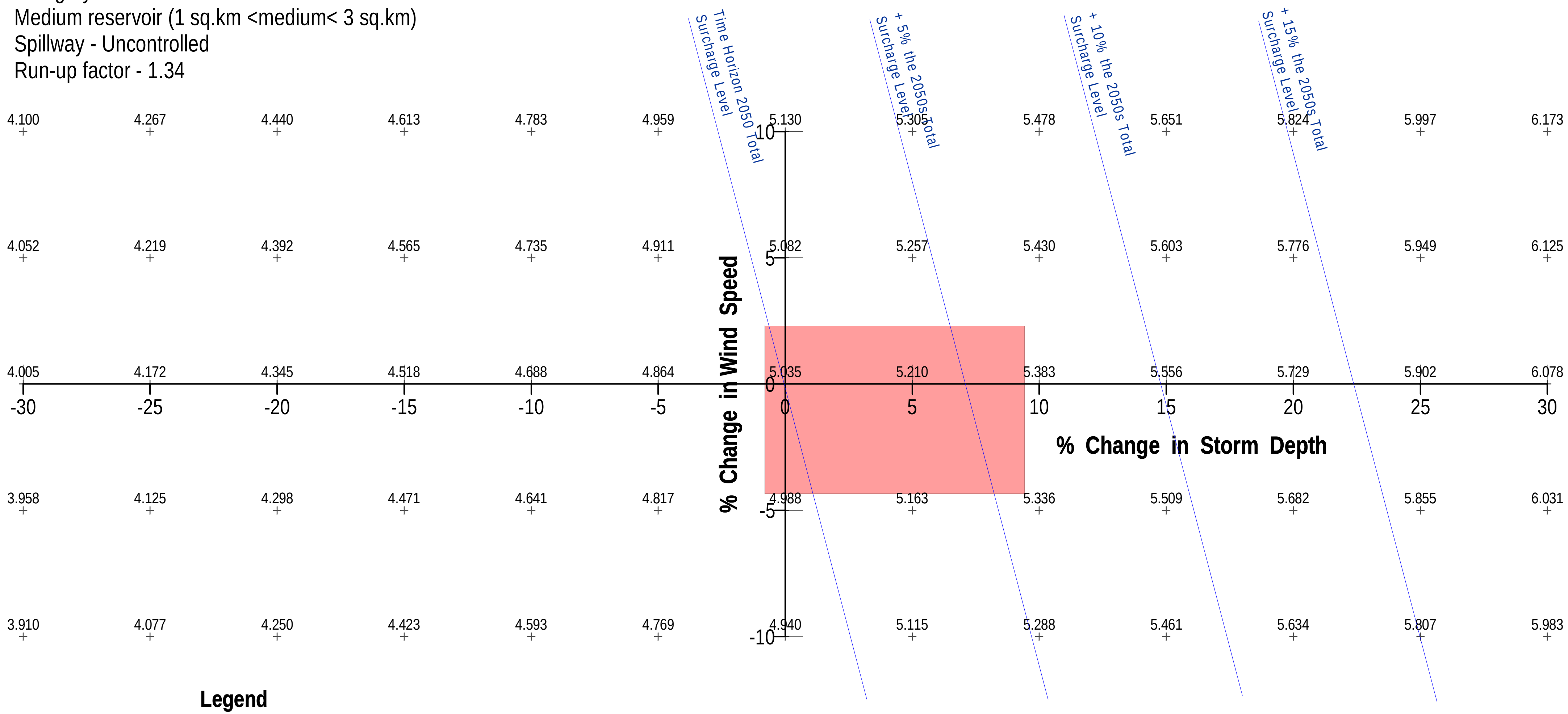
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 8 - Winter PMF

Wales
Category A
Medium reservoir (1 sq.km <medium< 3 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.34




**Legend**

5.035 + Modelled total surcharge (m)

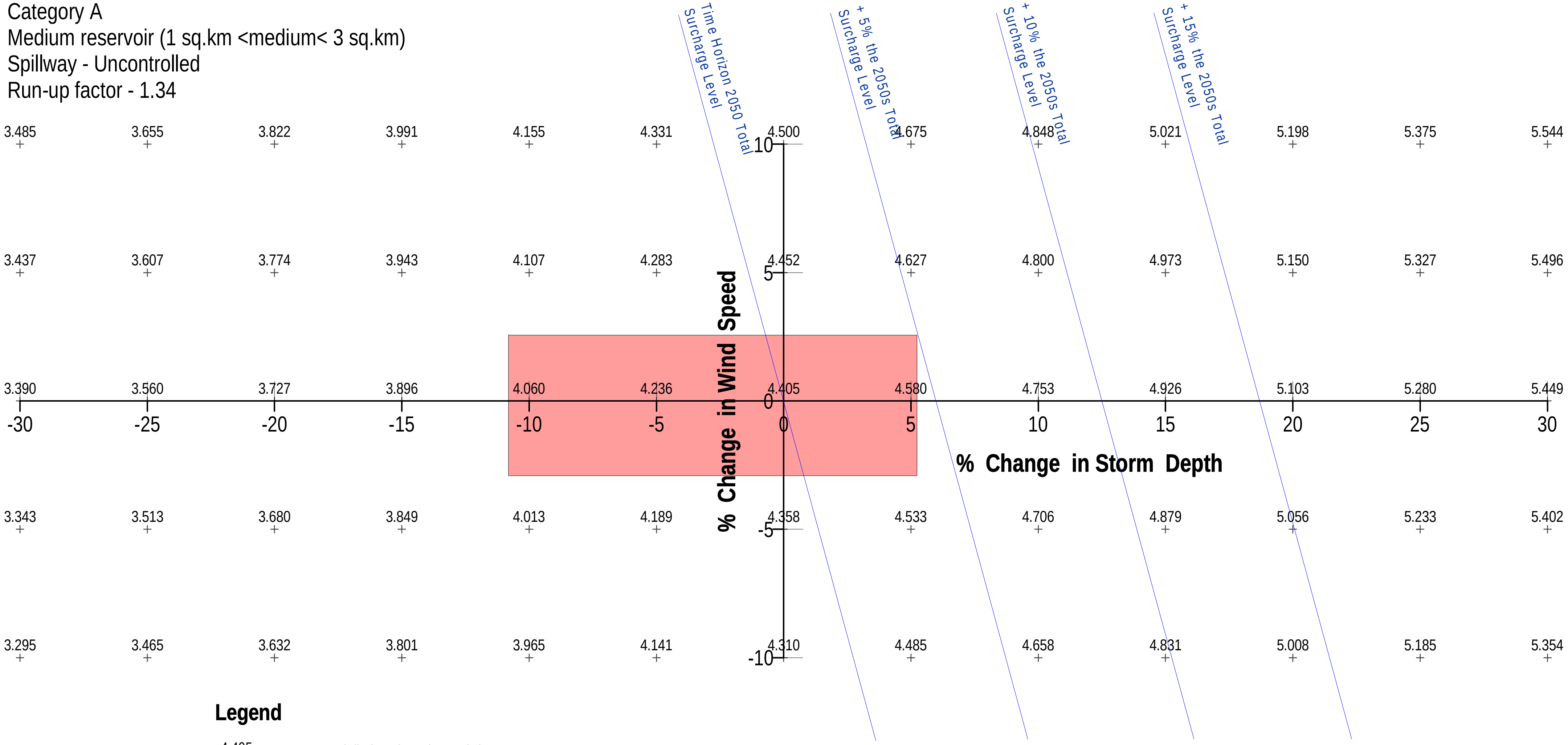
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 8 - Summer PMF

Wales
Category A
Medium reservoir (1 sq.km <medium< 3 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.34




**Legend**

4.405 + Modelled total surcharge (m)

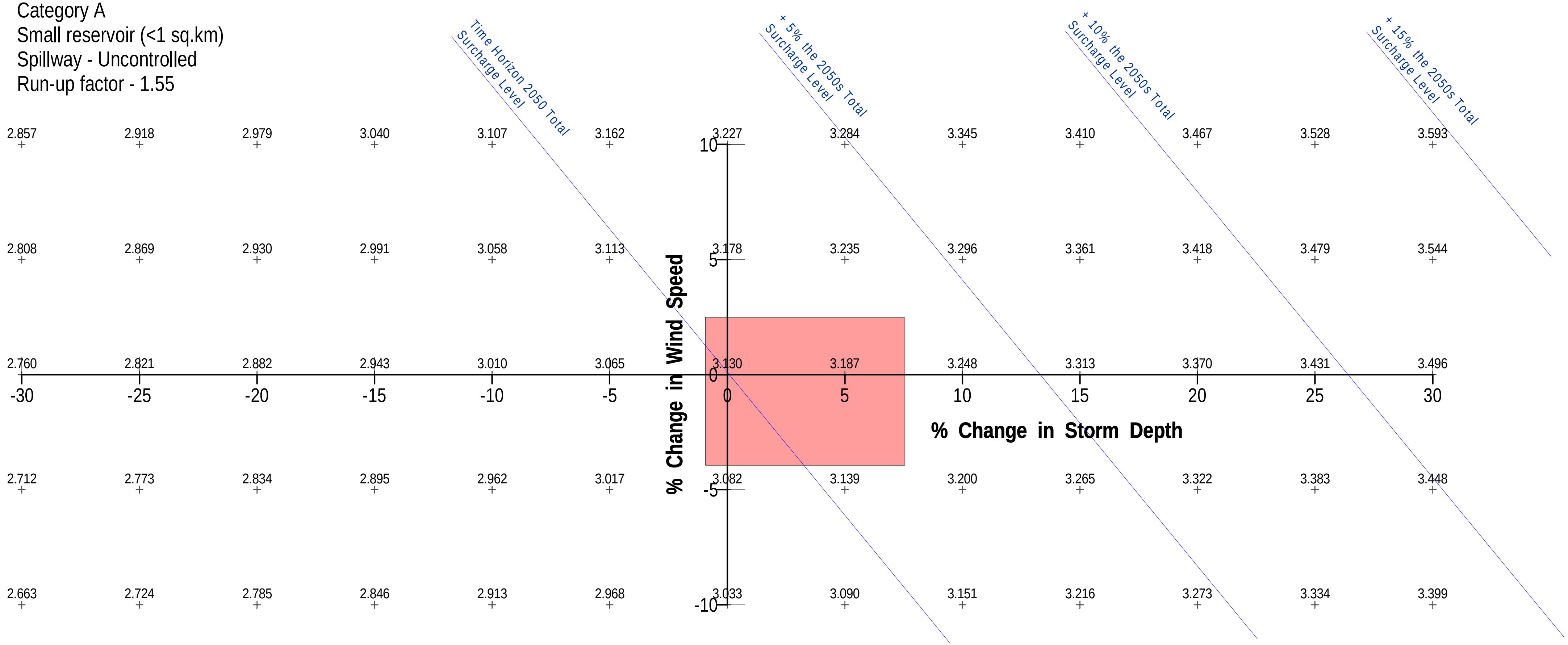
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 9 - Winter PMF

Wales
Category A
Small reservoir (<1 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.55




## Legend

3.130 + Modelled total surcharge (m)

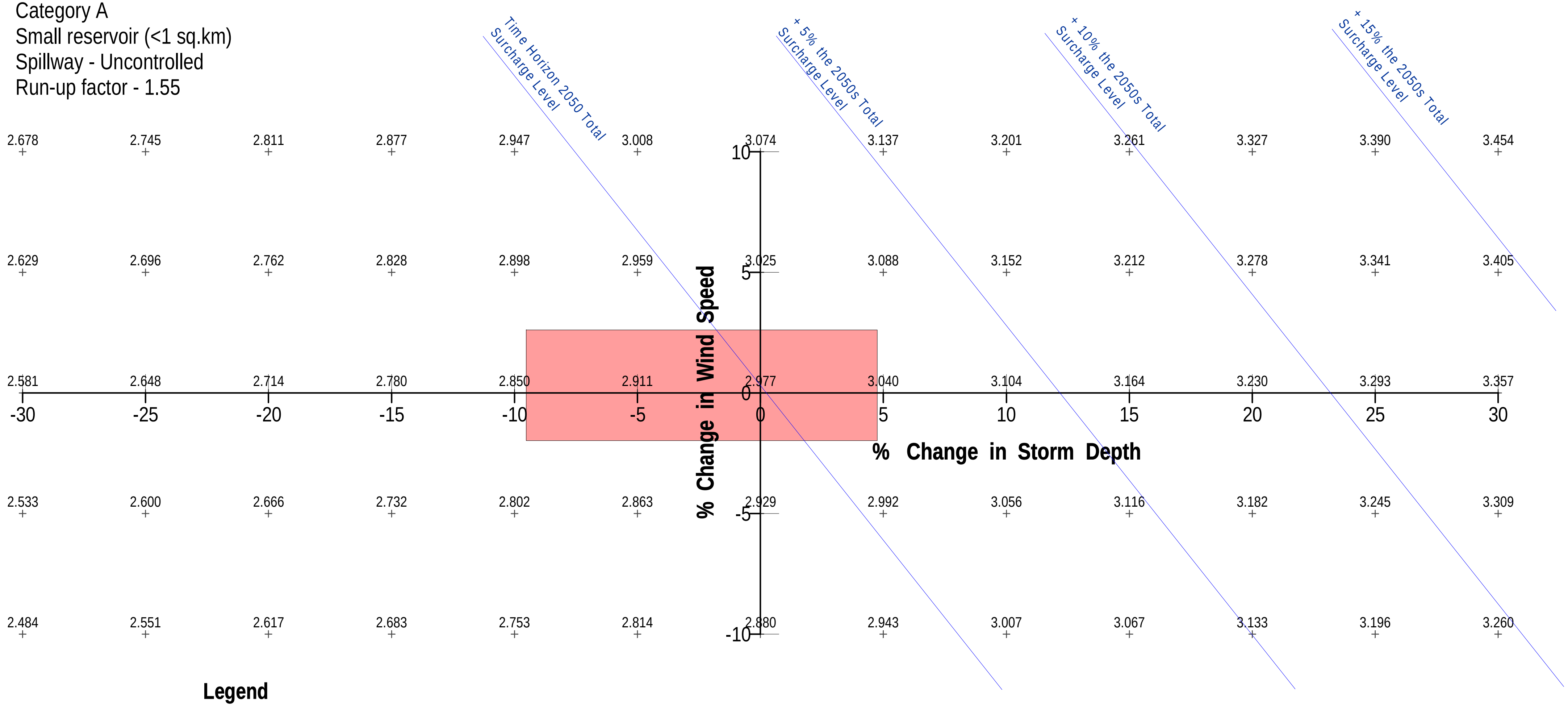
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 9 - Summer PMF

Wales
Category A
Small reservoir (<1 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.55




**Legend**

2.977 + Modelled total surcharge (m)

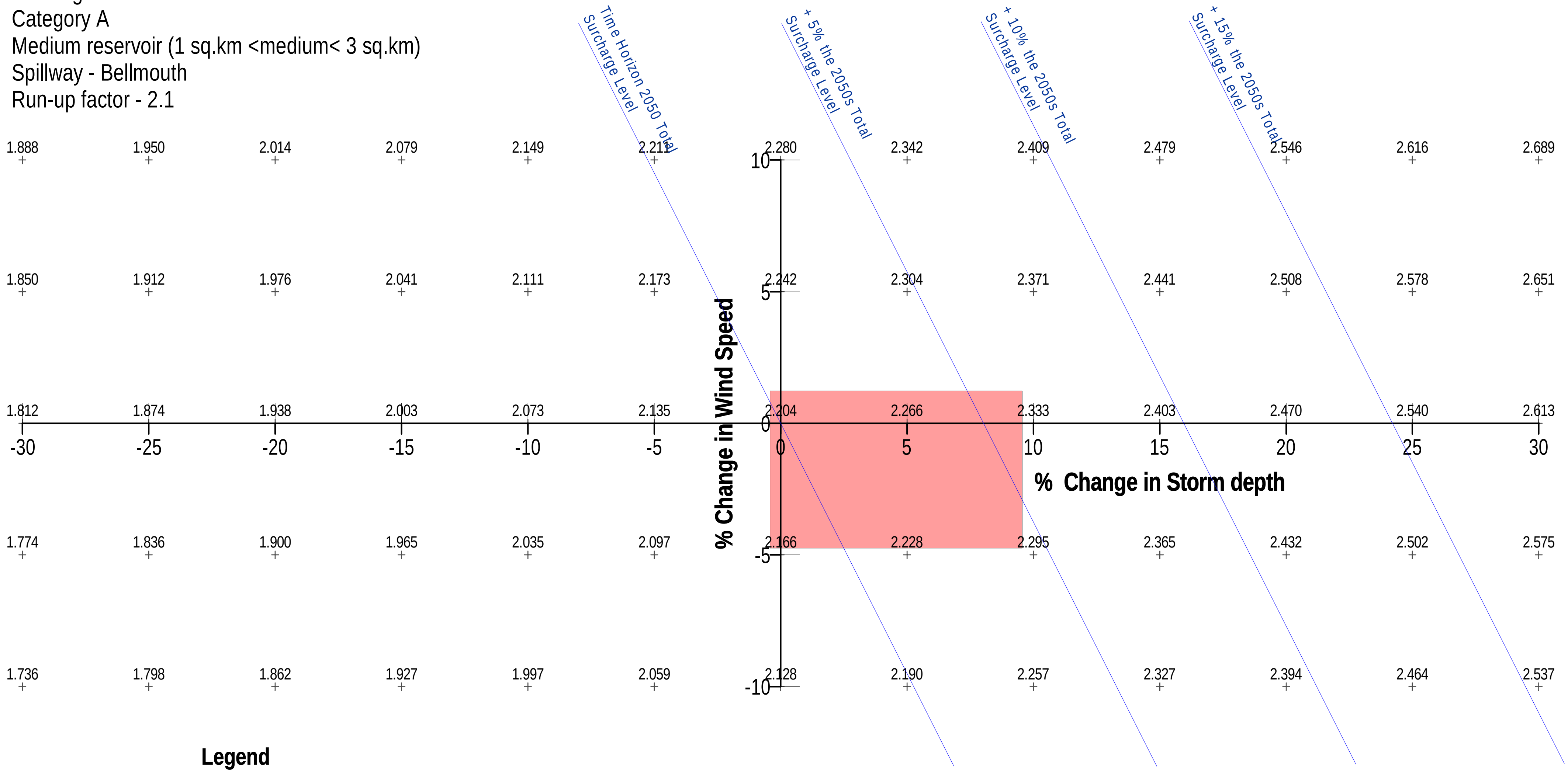
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 10 - Winter PMF

SW England
Category A
Medium reservoir (1 sq.km <medium< 3 sq.km)
Spillway - Bellmouth
Run-up factor - 2.1




## Legend

2.204 + Modelled total surcharge (m)

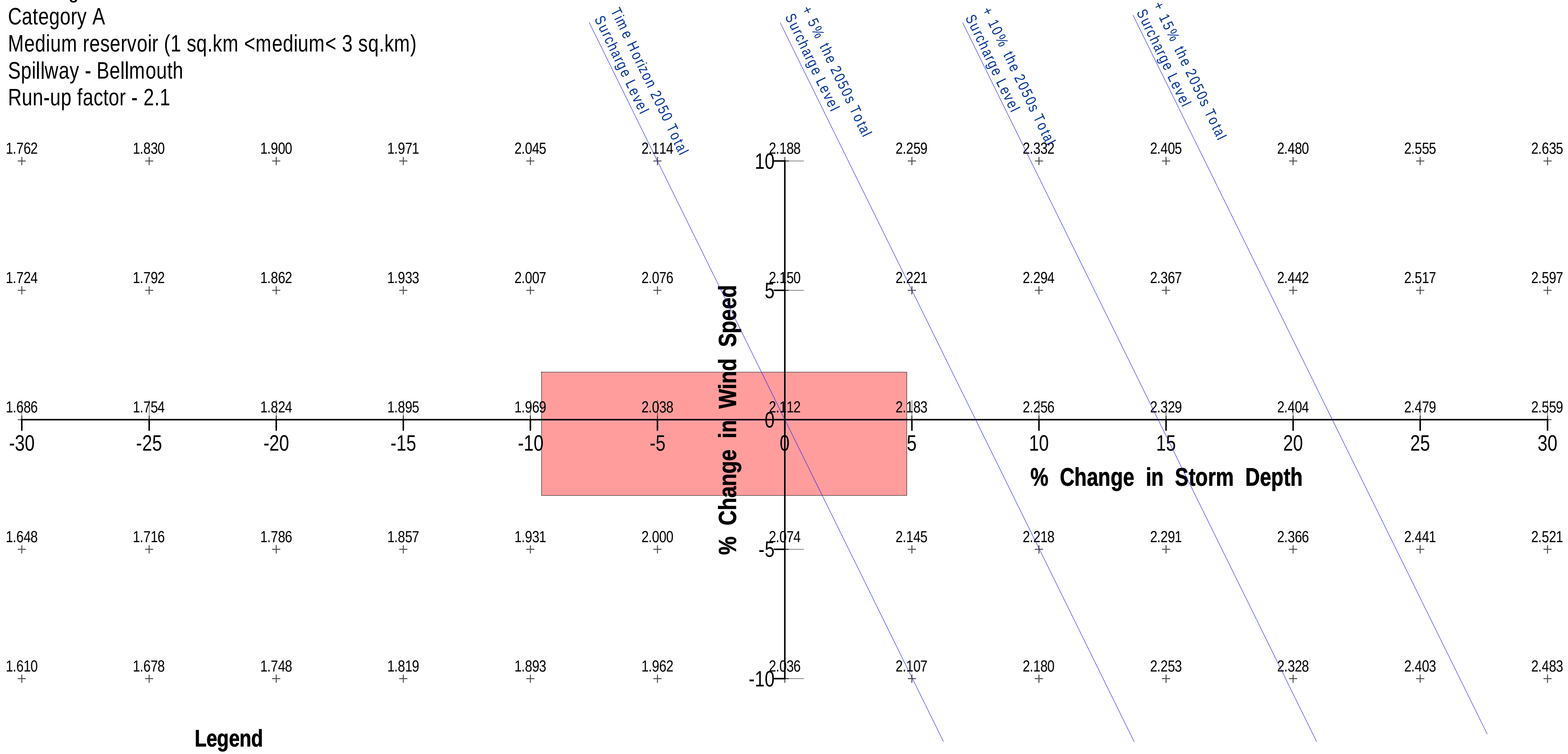
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 10 - Summer PMF

SW England
Category A
Medium reservoir (1 sq.km <medium< 3 sq.km)
Spillway - Bellmouth
Run-up factor - 2.1




### Legend

2.112 + Modelled total surcharge (m)

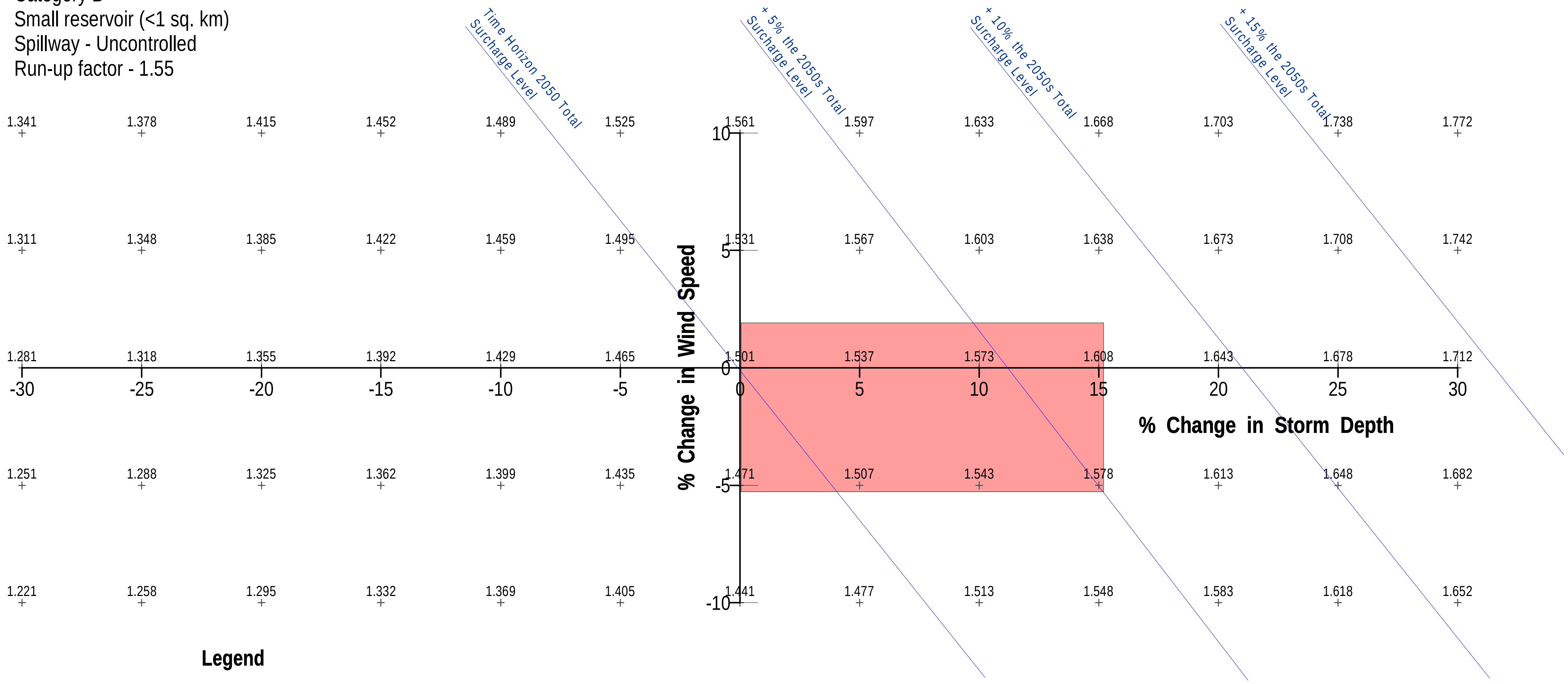
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 11 - Winter 10,000 Year

SW England
Category B
Small reservoir (<1 sq. km)
Spillway - Uncontrolled
Run-up factor - 1.55




### Legend

1.501 +   Modelled total surcharge (m)

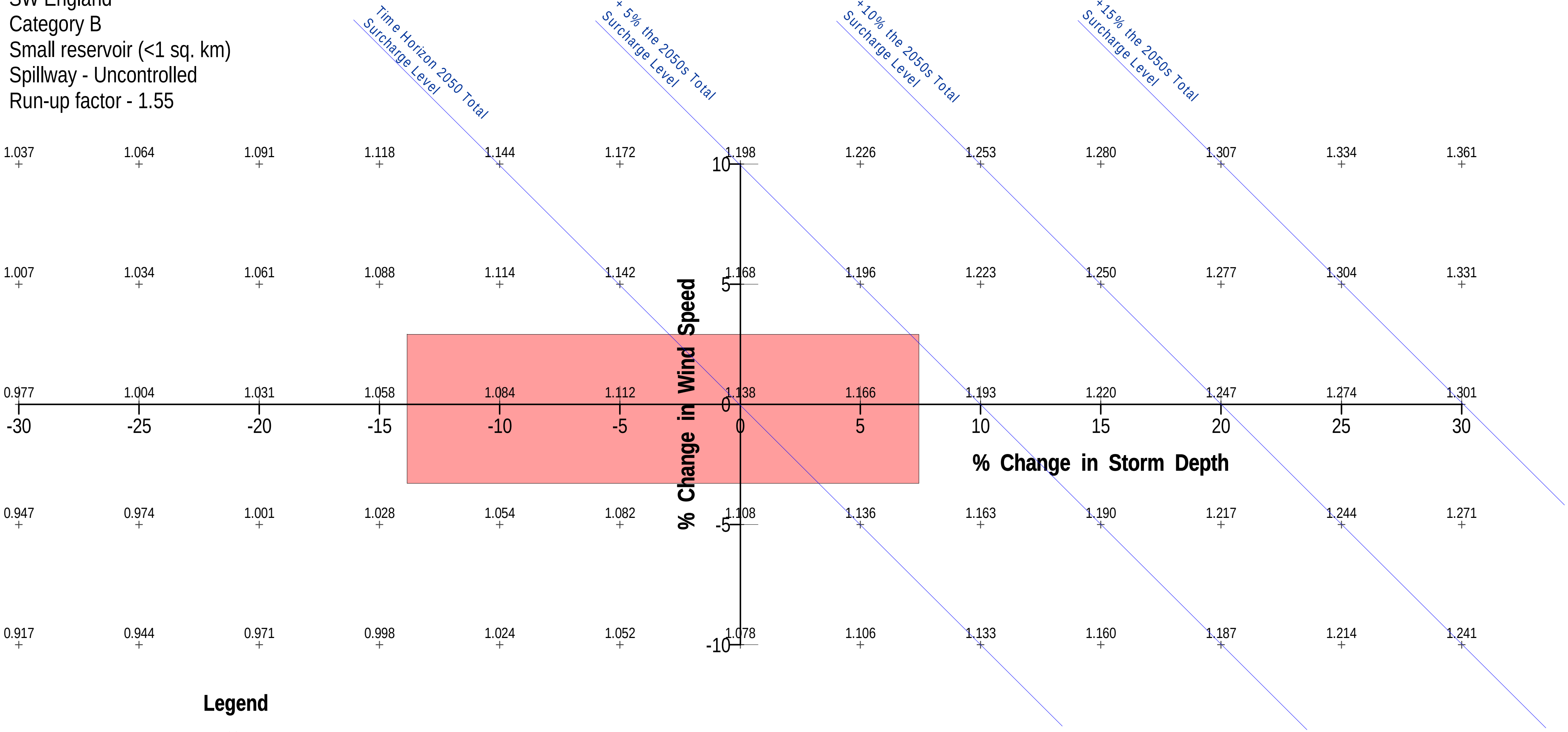
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 11 - Summer 10,000 Year

SW England
Category B
Small reservoir (<1 sq. km)
Spillway - Uncontrolled
Run-up factor - 1.55




## Legend

1.138 + Modelled total surcharge (m)

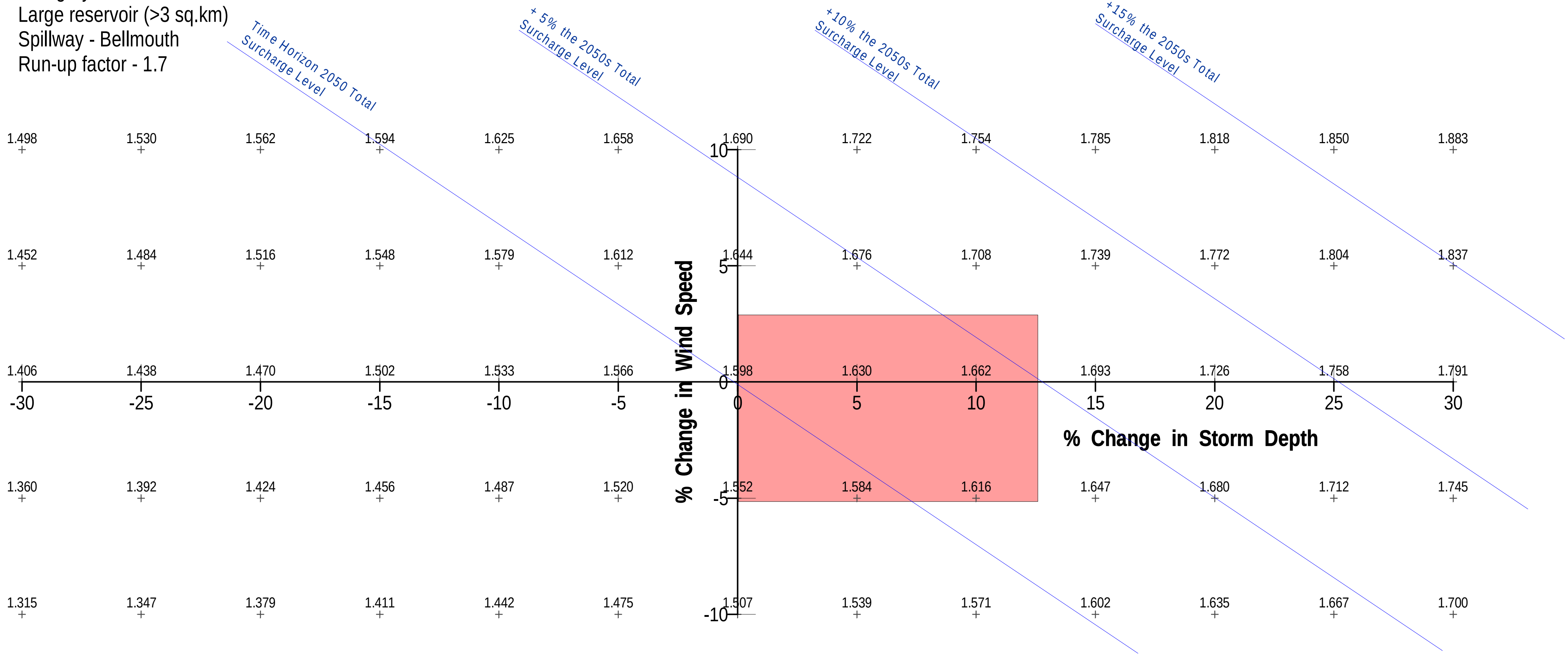
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 12 - Winter PMF

SE England
Category A
Large reservoir (>3 sq.km)
Spillway - Bellmouth
Run-up factor - 1.7




### Legend

1.589 + Modelled total surcharge (m)

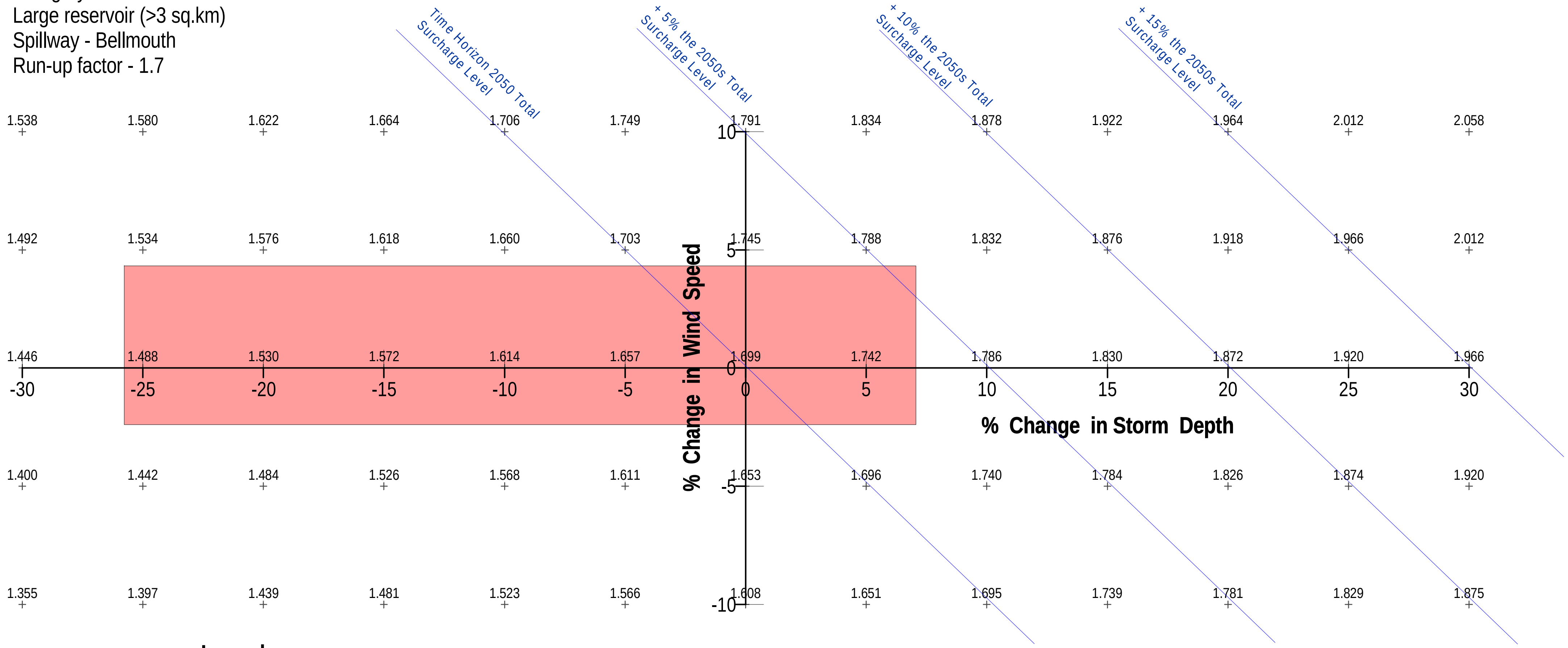
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 12 - Summer PMF

SE England
Category A
Large reservoir (>3 sq.km)
Spillway - Bellmouth
Run-up factor - 1.7




**Legend**

1.699 + Modelled total surcharge (m)

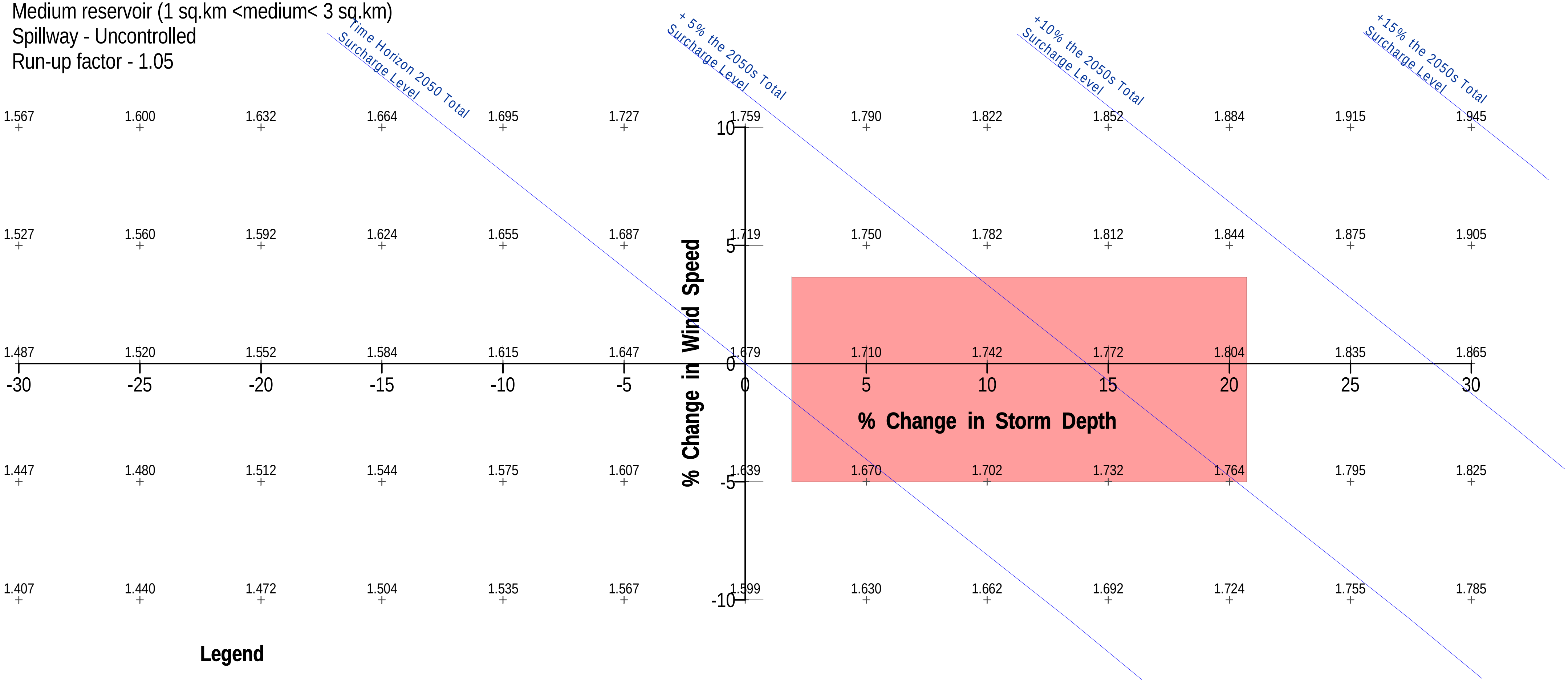
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Reservoir No. 13 - Winter PMF

SE England
Category A
Medium reservoir (1 sq.km <medium< 3 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.05




**Legend**

1.679 + Modelled total surcharge (m)

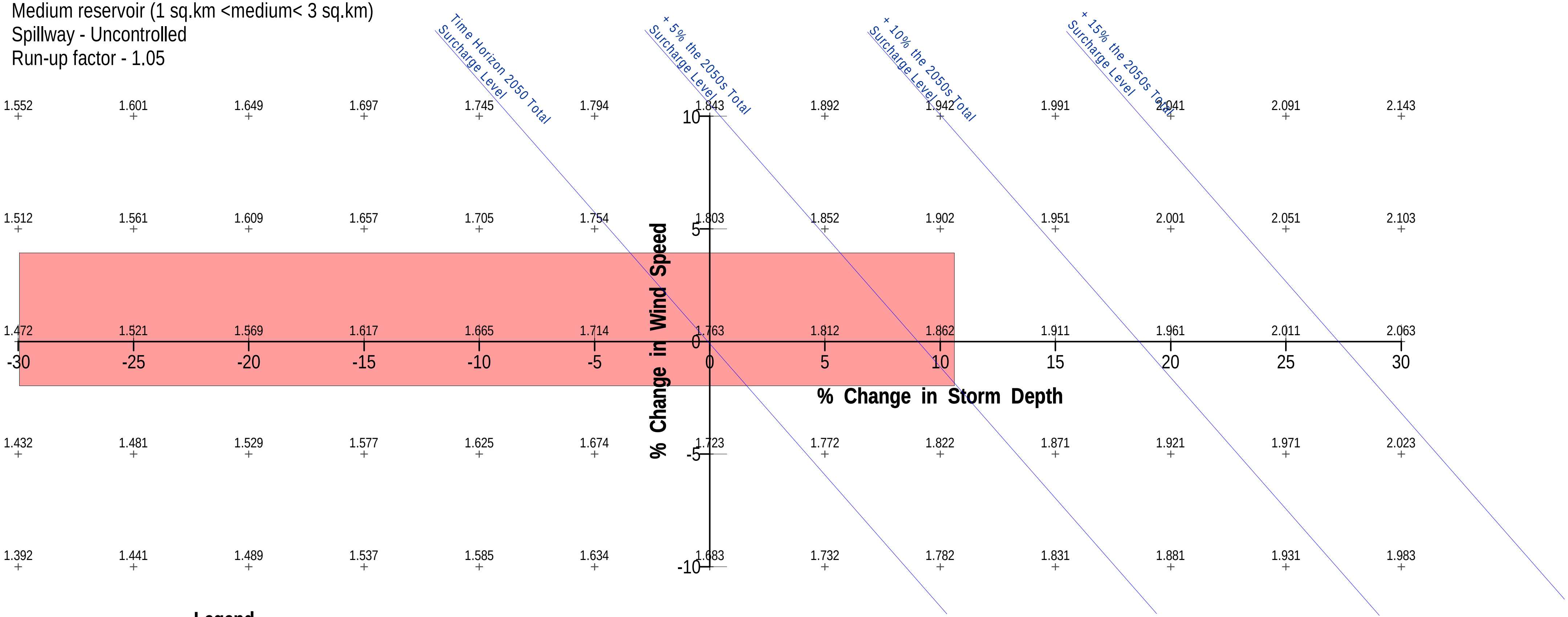
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 13 - Summer PMF

SE England
Category A
Medium reservoir (1 sq.km <medium< 3 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.05




**Legend**

1.763 + Modelled total surcharge (m)

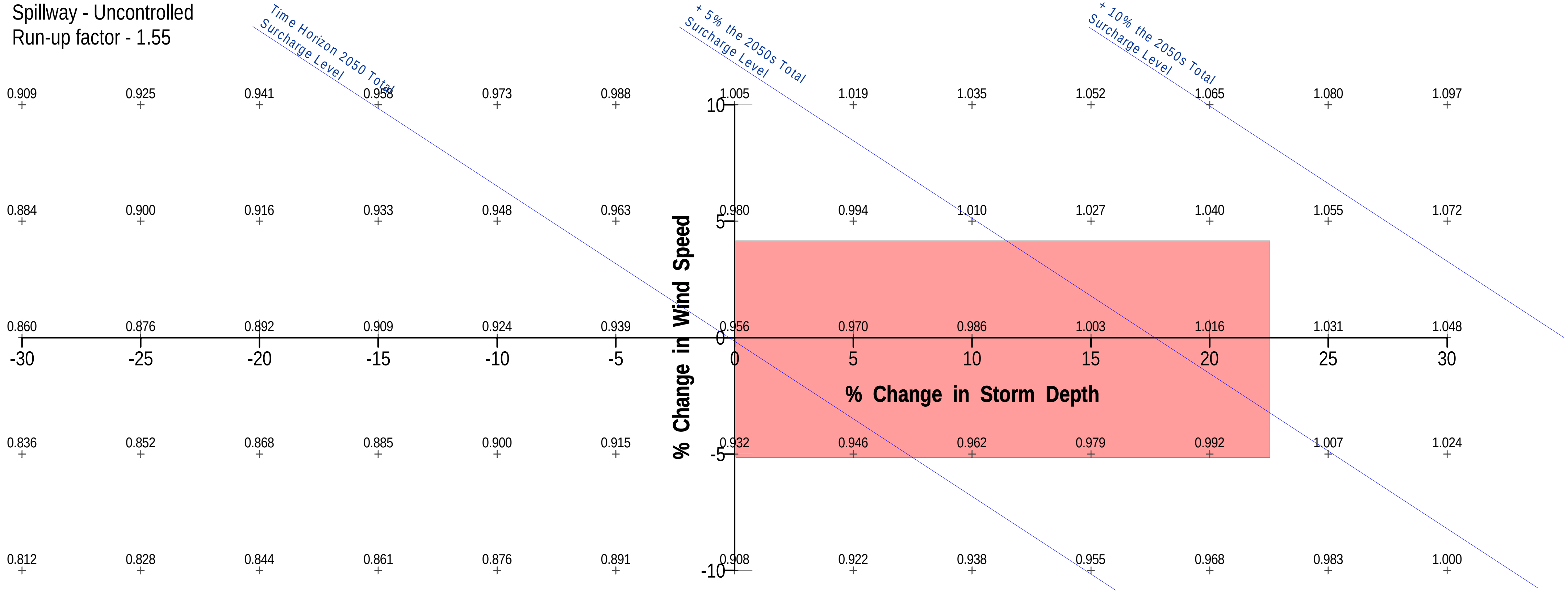
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 14 - Winter 1,000 Year

SE England
Category C
Small reservoir (<1 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.55




**Legend**

0.956 + Modelled total surcharge (m)

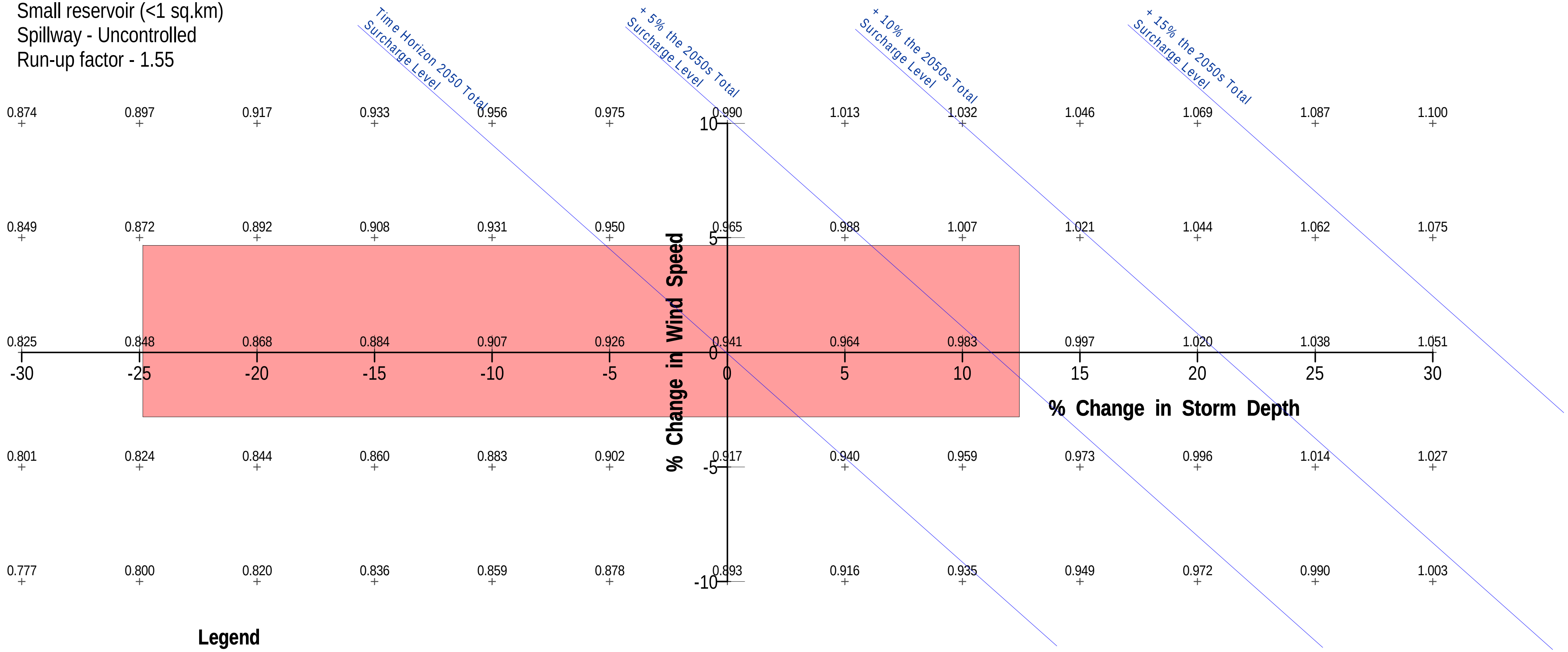
Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:**
(1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

## Reservoir No. 14 - Summer 1,000 Year

SE England
Category C
Small reservoir (<1 sq.km)
Spillway - Uncontrolled
Run-up factor - 1.55




### Legend

0.941
+
Modelled total surcharge (m)

Seasonal climate change envelope - potential range of change according to climate change model (Time Horizon 2050)

Line of constant level

**Notes:** (1) Total surcharge is stillwater flood rise + wave run-up
(2) Infinite freeboard assumed for sensitivity presentation
(3) Climate change scenarios used were UKCIP98

# Appendix G

## Analysis of Maximum Percentage Changes in Total Surcharge

## Appendix G - Analysis of Maximum Percentage Changes in Total Surcharge

Results of the total surcharge sensitivity analysis for the 2050s are presented, in which the event rainfall depth and the wind speed were incrementally changed.

Figure 1 shows the relationship between geographic and climatic regions and the maximum percentage predictions of the total surcharge in the 2050s but the results show a 5 to 10 percentage change in total surcharge for the 2050s with the majority of sites located in medium risk.

Figure 2 plotting dam category with respect to maximum percentage change and total surcharge shows no particular relationship.

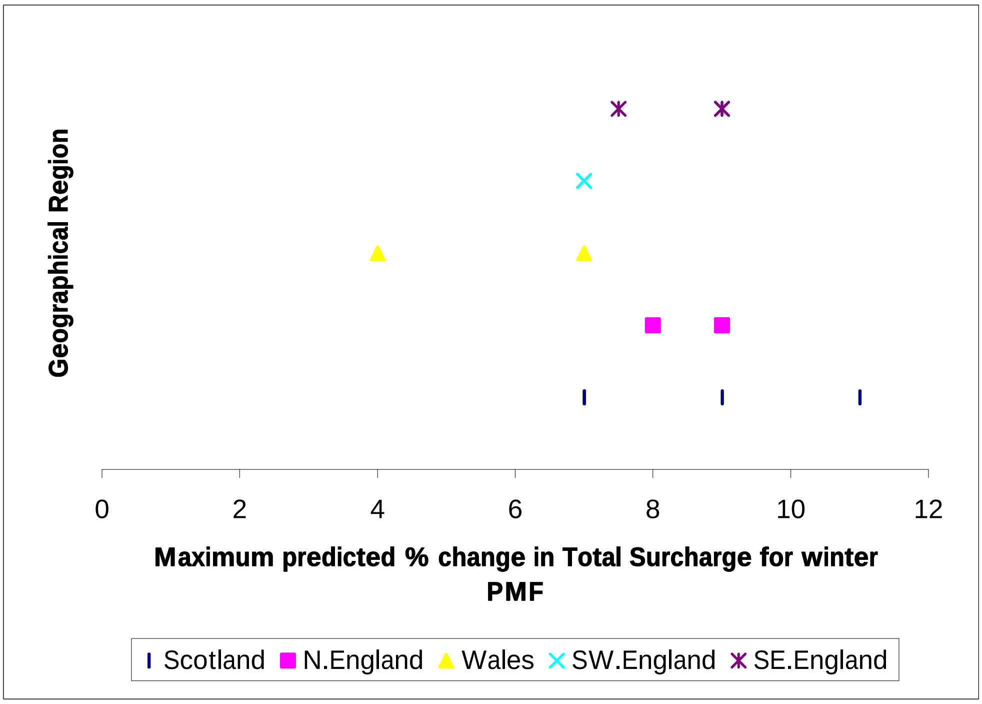
A comparison of reservoir size with maximum predicted percent change in total surcharge is shown in Figure 3. This shows a random plot with no significant size of reservoir at high risk.

Figure 4 shows a plot of spillway type against the maximum predicted percentage change in total surcharge. In general uncontrolled spillways are at least and greatest risk. Bellmouths are free flowing and not drowned with intermediate risk. Winter and summer floods are of similar behaviour for spillways.

Figure 5 shows that run-up factor plotted against the maximum predicted percentage change in total surcharge is not conclusive as again the geographic/climatic location is more significant.

The dams were grouped into three age zones, pre 1900, 1900 to 1945 and 1950 to present.
Fig 6 shows the age of the dam against predicted percentage change in total surcharge. The oldest stock of dams in the selection do not show a higher percentage change in total surcharge.

It should be noted that only changes in average precipitation intensity and wind speed have been considered and not changes in the maximum precipitation and wind speed.



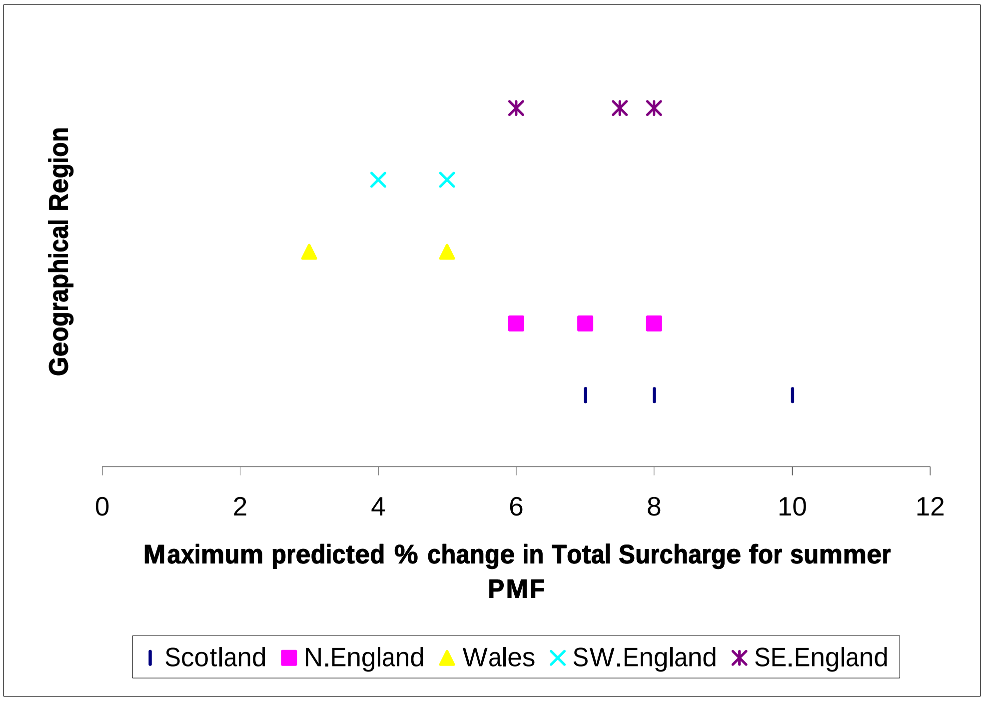
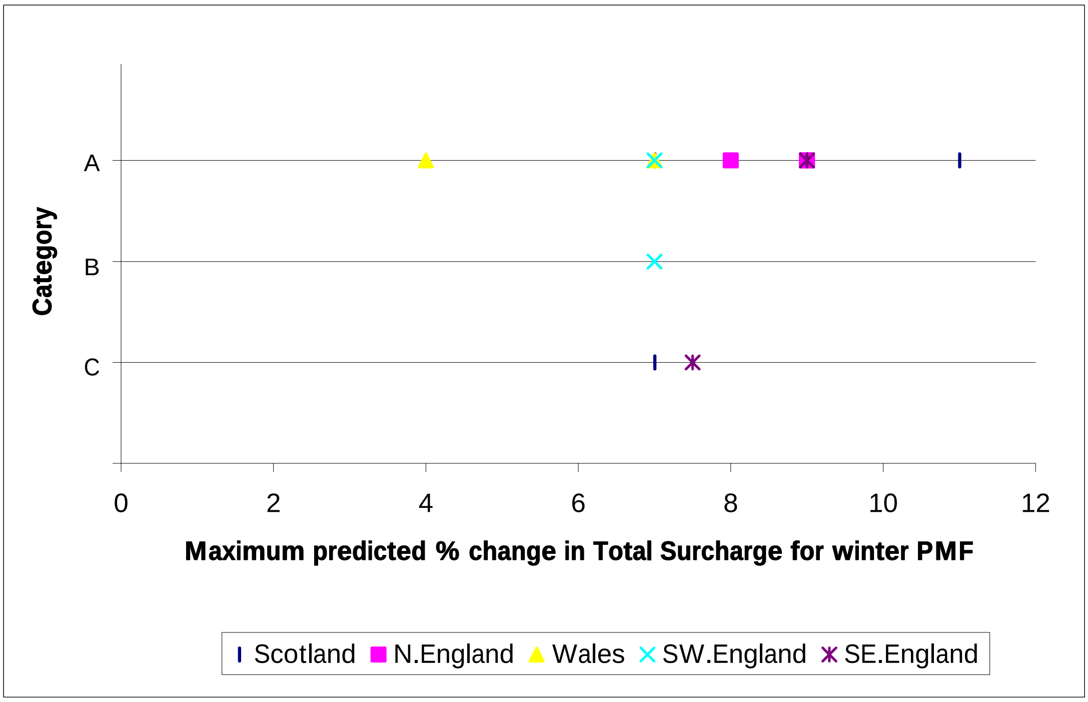




Fig 1: Association between Geographical /Climate Region and maximum predicted percentage change in Total Surcharge



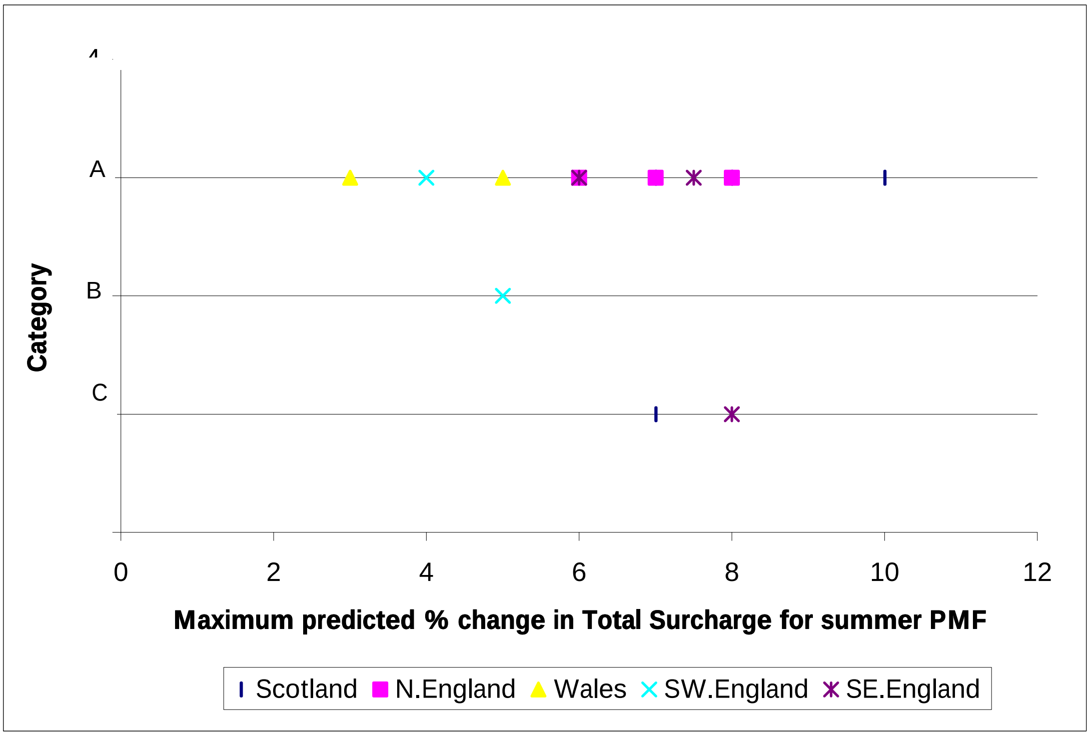




Fig 2: Association between Dam Category and maximum predicted percentage change in Total Surcharge

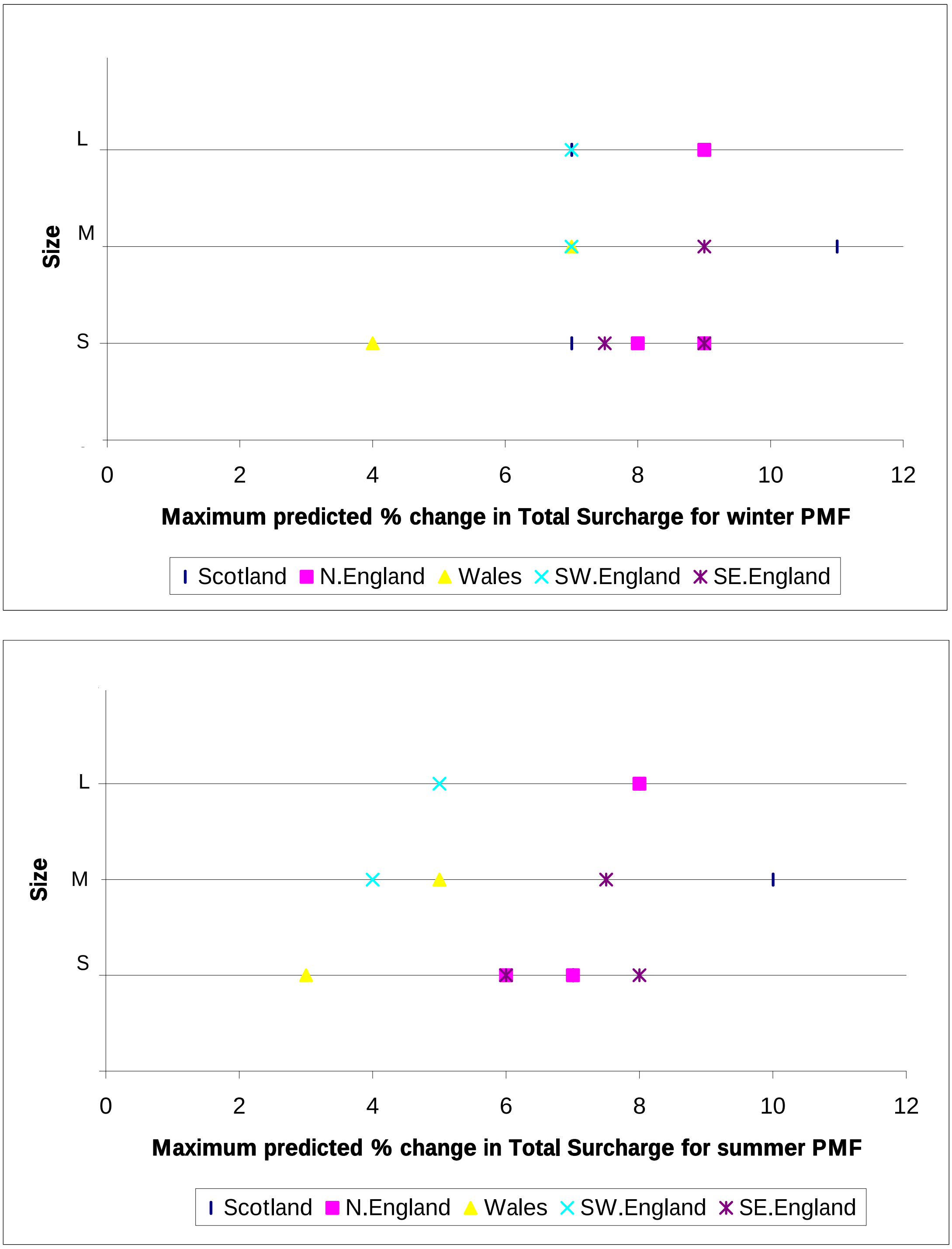
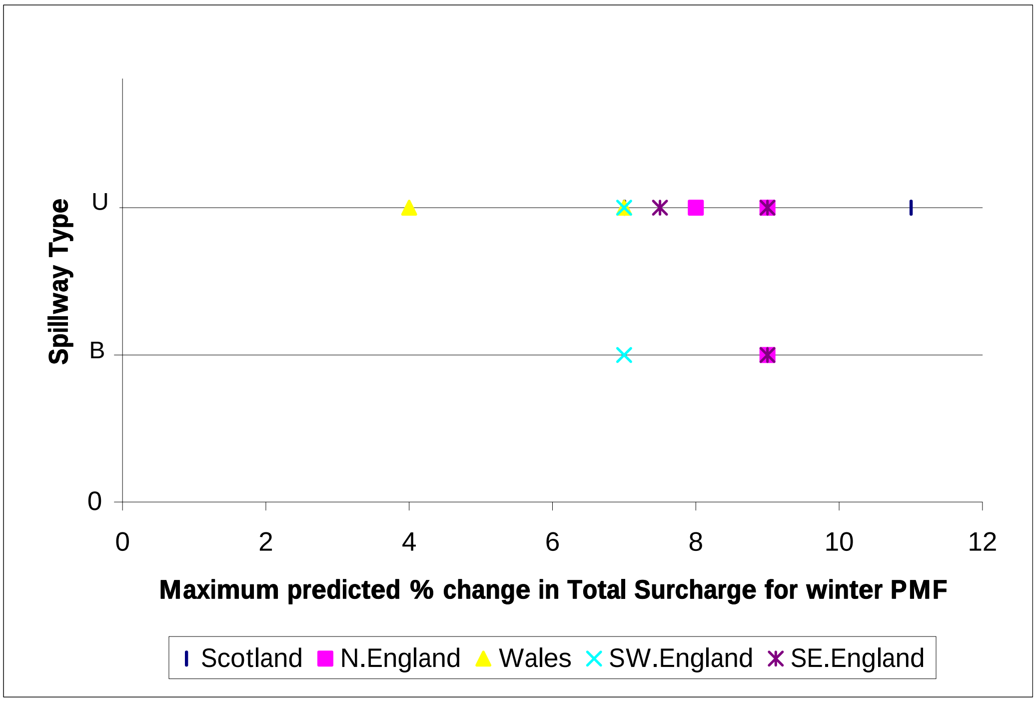



Fig 3: Association between reservoir size and the maximum predicted percentage change in Total Surcharge



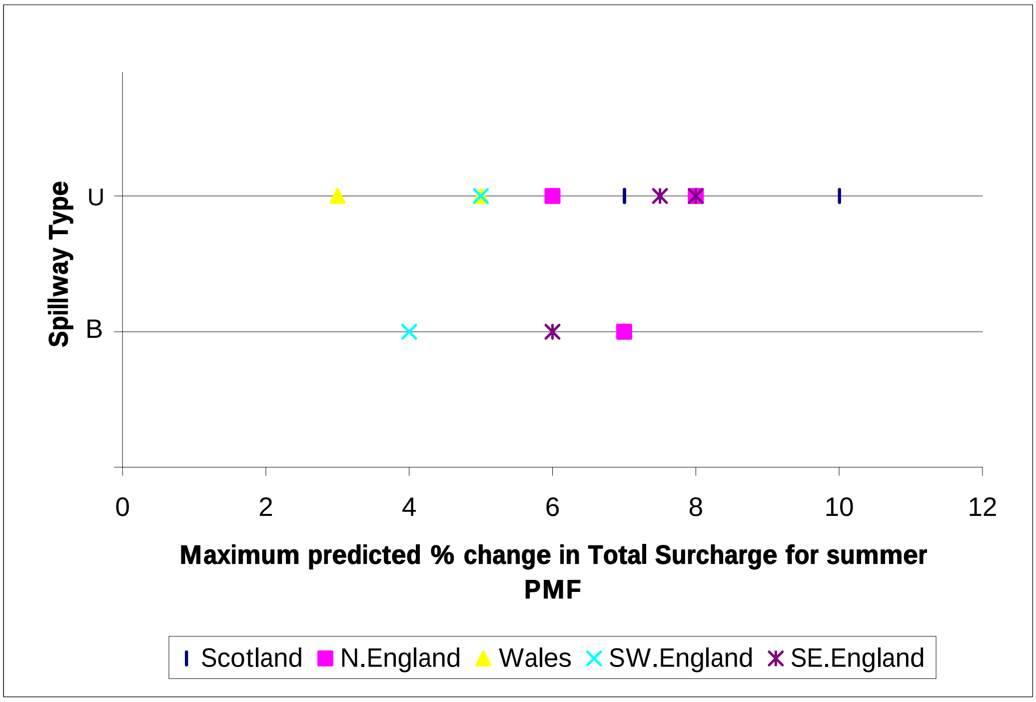
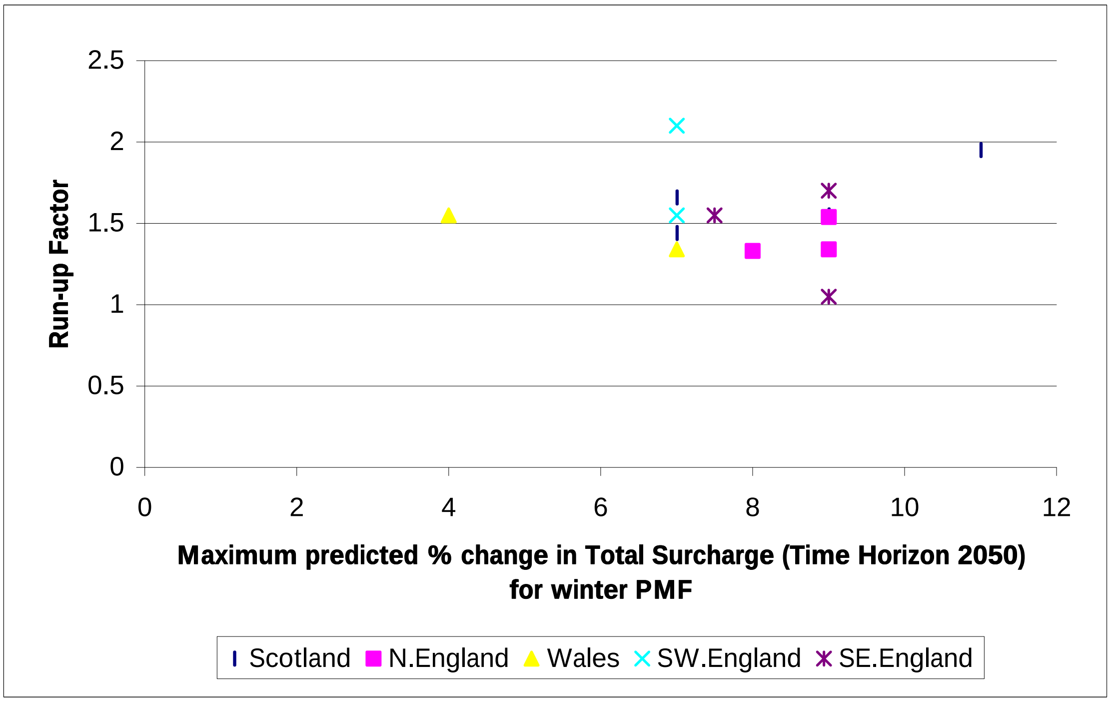




Fig 4: Association between spillway type and the maximum predicted percentage change in Total Surcharge

U - Uncontrolled
B - Bellmouth



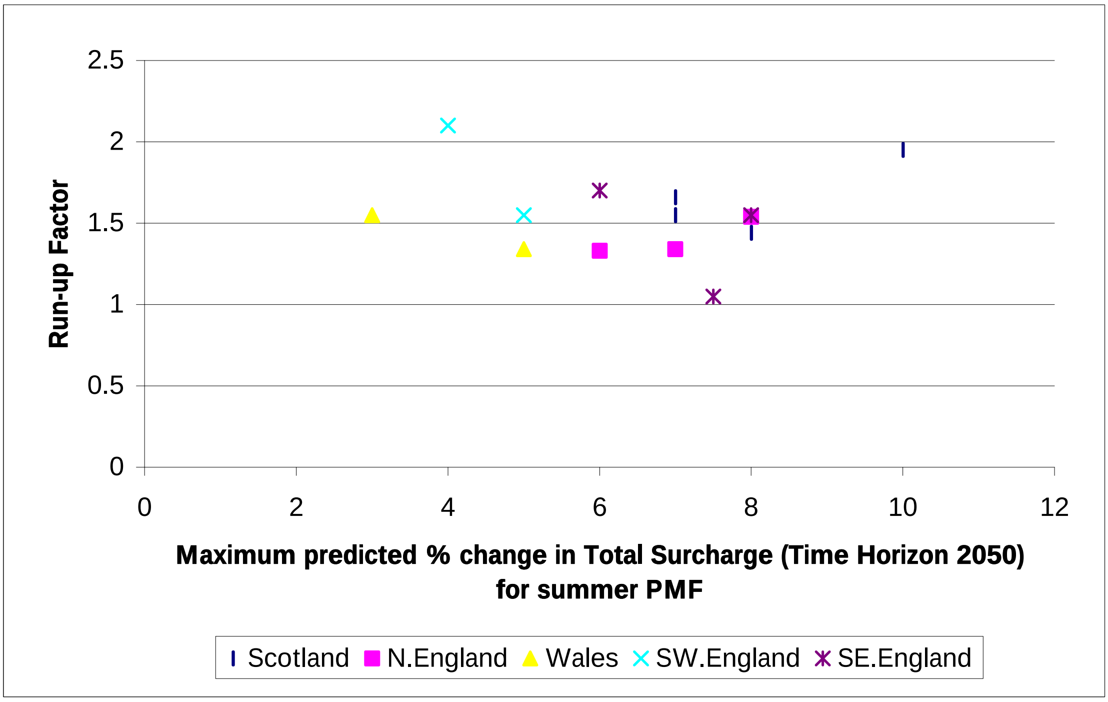
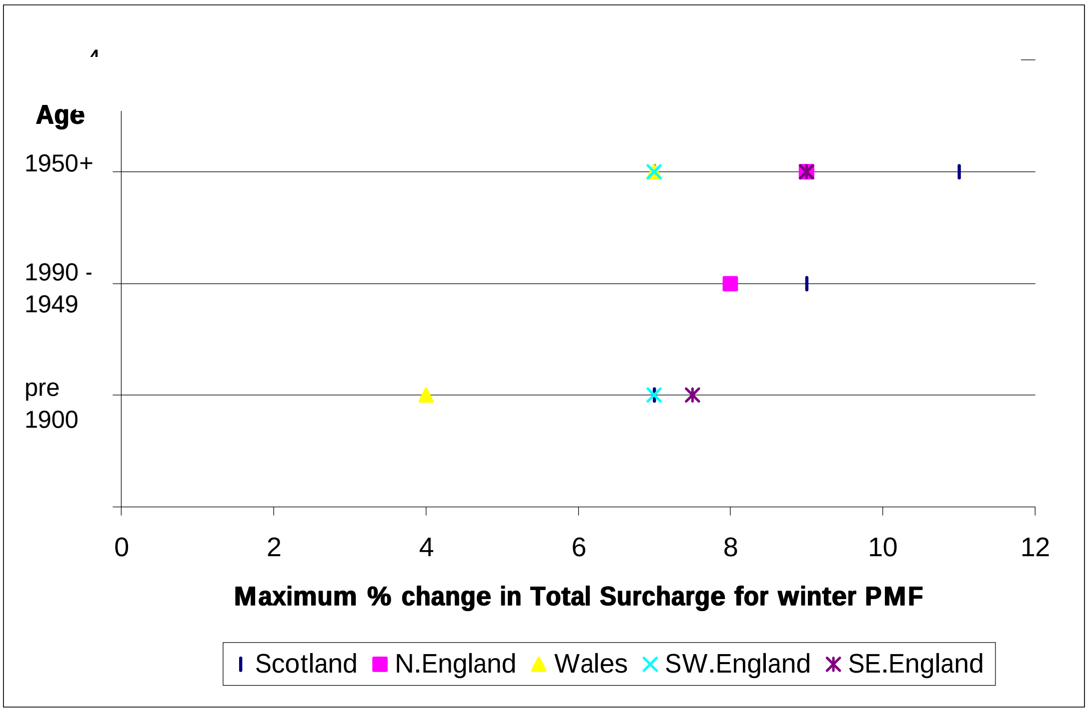




Fig 5: Association between run-up factor and the maximum predicted percentage change in Total Surcharge



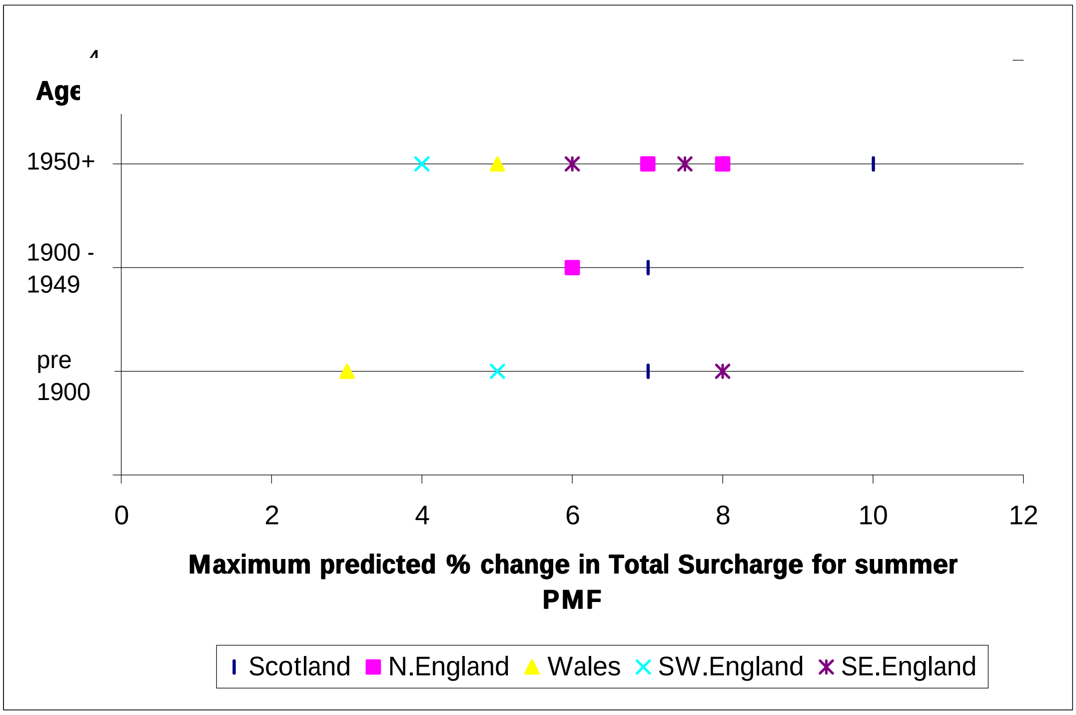




Fig 6: Association between age and the maximum predicted percentage change in Total Surcharge