DETR

Dam Safety Research - Climate Change Impacts

Advice Note on Rainfall induced instability of Dam Embankments

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17 January 2003

Mr K Bates
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Dear Mr Bates

Research Contract
Climate Change Impacts on the Safety of British Reservoirs
Supplementary Report

We refer to the Department's letter of 5 January 2001, reference Area 1-1 (WS 194/-/2/24) confirming your agreement to vary the above contract for undertaking a supplementary report.

We have pleasure in submitting our Final Report on Climate Change Impacts on the Safety of British Reservoirs - Advice Note on Rainfall induced instability of Dam Embankments.

Yours sincerely

J W Findlay
Technical Director

WRD

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Executive Summary

In response to media interest in the views of the insurance industry on aspects of climate change, DETR (now DEFRA) commissioned a review of the circumstances that might lead to vulnerability of UK dam embankments due to increased direct rainfall acting on their surface.

The concerns are based on more intense storm rainfall and extended periods of wetter weather. The review considered rainfall-induced mechanisms (principally due to saturation and erosion) from a geotechnical (vulnerability) and hydrological (likelihood) perspective. The key concern of increasing rainfall is greater saturation, higher pore pressures within the fill and a resulting loss of strength of the fill in general and the embankment as a whole.

Dam embankments differ significantly in their potential response to heavy rainfall from other infrastructure embankments (road and rail) due to the design intention to retain water. They are thus already partially saturated by design and have features to deal with internal water seepage.

Consideration of changing hydrology relevant to dam embankment stability covers point rainfall intensities, storm rainfall depths, seasonal rainfall depths, rainfall frequency and evaporative losses.

There is considerable regional variation of these characteristics under the present UK climate profile such that many dam embankment sites are already exposed to a range of extremes that may not vary greatly with climate change.

A typical UK embankment dam of well-grassed cohesive fill was the main focus of the review. Many UK dams are of this type and are also more than 50 years old such that absence of modern design features, particularly drainage, are a major consideration. Granular fill embankments are considered less of a concern.

Some embankments are vulnerable to instability as a result of adverse fill properties but most are tolerant of surface infiltration. Many dams have a resistance to infiltration through the design detailing of their crest and downstream slope.

In terms of extreme rainfall some embankments have historically been exposed to potentially limiting conditions of point intensity and seasonal depth. It is therefore possible that the infiltration capacity of some dams of most types has already been exceeded under present/historic conditions. The performance history of these dams would thus reveal if there is a potential problem from increased precipitation. Confidence in the typical performance of other dams can be drawn from this.

Deep-seated instability is the greatest risk to dam safety. Shallow slips are not uncommon and increased rainfall will make these more likely though safety is not so likely to be compromised. There is no strong evidence of deep-seated problems due to extreme rainfall. Heavy rainfall even now creates localised erosion problems where run-off control is unsatisfactory but again safety is usually not a major issue.

There is a possible phenomenon associated with dam embankments where permeability decreases with depth and infiltration flow is vertical. Few fills are susceptible to this characteristic and the number of dams at risk may be very small. Some of those that are at risk may already have experienced maximum possible adverse conditions under historical climatic conditions (maximum winter infiltration).

The key issue is whether there is part of the dam population that is particularly vulnerable by virtue of type but has not been exposed to historic extremes due to regional differences in design and climate. This will require further research to quantify.

There will, however, always be marginally stable dam embankments with site specific features that could be adversely affected by heavy rainfall. Climate change is unlikely to add significantly to the risk already posed by UK storms of historic magnitude.

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1. Introduction

1.1 Brief

Babtie Group were commissioned by DETR (now DEFRA) to produce a research report on climate change impacts on UK reservoirs. This work focussed on floods and was issued to DEFRA as a final report in January 2002. An extension to this work was commissioned in January 2001 to comment specifically on rainfall effects on embankment stability. Reference to the climate change report will provide background reading to Section 3 of this report.

Recent media reporting of insurance industry views suggested that embankment dams might be vulnerable to the effects of increased rainfall on their surface and that the predictions of climate change might therefore cast doubt on their future integrity. DETR are anxious to respond in an authoritative way to this suggestion and therefore require a report on the key issues.

The brief sets the following question:
"Does the prolonged heavy rainfall envisaged under climate change scenarios (and, coincidentally, perhaps experienced over much of England and Wales in the autumn of 2000) present a threat to the stability of existing earth embankment dams in Great Britain."

This report therefore reviews the current and future vulnerability of UK dam embankments to extreme rainfall.

1.2 Overview of UK situation

Climate change scenarios suggest that at least parts of the UK may become wetter. In addressing the question raised in the brief, the geotechnical and hydrological response characteristics of UK embankment dams have been reviewed. This relates principally to the rainfall-initiated mechanisms by which failure could occur i.e. saturation and erosion although groundwater rise may be a peripheral issue. This raises a number of key questions related to why embankments currently become unstable and the influence of rainfall on this.

The nature of climate change in the UK of concern to this study is expressed as more intense storm rainfall and generally wetter longer-term conditions. This could influence the overall soil moisture relationship on which embankment strength depends.

Many very old UK embankment dams are built of clayey material and this has positive and negative implications. Well-grassed clay slopes will have a high resistance to erosion but slopes become weaker with saturation. Almost all UK embankment dams are protected to some degree on the crest and downstream slope. Many are grassed and some are surfaced and drained along the crest. A few will have drainage systems within the downstream slope and depending on type and configuration this can have a positive or negative effect on sub-surface infiltration. The inherent (generic) strengths and weaknesses of UK dams provide degrees of both confidence and concern in relation to rain induced instability. Some old embankments have more granular shells supporting puddle cores and cohesive transition zones. While granular shells are potentially more vulnerable to erosion the UK practice of well-cropped grass cover mitigates against this. A number of more modern embankment dams have been built with granular fill but this is judged to be less sensitive to changes in rainfall.

One of the key questions is to ask whether there is a current problem with rainfall induced instability. There have been instances of deep seated slope failures in dam embankments in the UK however these are most often related to design inadequacies (weakness) in the embankment or foundation material or to seepage generated pore pressures driven by the reservoir head. There are instances of superficial downstream slope failures due to saturated weak material but there is not at this time a significant slope stability problem apparent amongst the stock of UK dams, although there is some concern that there may be potential for latent instability. Generally, in the context of this review, the concern would only apply to downstream slopes as upstream slopes are effectively saturated in the normal operational case.

A proportion of UK dam embankments will have a low factor of safety (FOS) against instability of the slopes and in some cases this low value may be a function of fill saturation.

A significant increase in rainfall might produce a response in stability terms. Initial consideration of this suggests that UK dams are tolerant of fairly high variations in regional rainfall and thus common types may not be that sensitive to climate-change.

Many UK embankments will remain vulnerable to instability with or without climate change effects on rainfall. Older embankments that have been raised with oversteepened slopes and narrow crests are particularly vulnerable. Dam embankment failures are rare but incidents do occur though few in recent years have resulted in a major risk of a breach. Most of those recorded have a major element of through bank seepage or concentrated run-off from adjacent land or features contributing to the damage.

1.3 Comments on Autumn 2000 events

The very wet episodes that led to extensive flooding in Autumn 2000 included a number of extreme storms as well as a general period of very wet weather. Both these features are associated with aspects of climate change and were linked with this by the media and many lay people.

This report shows that these events were not without historical precedent and therefore are not perhaps as significant as many people believe in terms of discrete rainfall events, and thus impact on individual structures (the cumulative flooding impact is a separate issue not discussed here)

In terms of reservoir safety the defining hydrological event recognised for ultimate design is the probable maximum flood (PMF). It is difficult to draw direct comparisons (as the PMF is a catchment wide event) but the measured individual storms of 2000 did not approach the point intensities that are theoretically possible (Estimated Maximum Precipitation, EMP). Although some reached 50% EMP. However, there is information on historical events that could represent a much higher proportion of EMP.

While a number of embankment structures were known to have suffered damage during the 2000 storms, these were cuttings and transportation embankments rather than dams. Such structures have small but significant design differences that make them more vulnerable than dams to intense or prolonged rainfall. Such differences are intentional and recognise the quite significant difference in hazard posed by embankment slips in these different categories. While these are incidental indicators they do illustrate the potential for the most marginal dam embankments to suffer distress during extreme events, particularly as some older dams had minimal design input.

1.4 Approach to Study

The approach adopted will present rainfall induced stability mechanisms in geotechnical terms followed by a commentary on hydrological conditions and meteorological events plus comparisons with selected reference situations. All of this will be in the form of a written discussion of the issues. While dam embankments have a range of safety factors due to varying geometry, design features and construction quality they can also be influenced by site specific features such as springs in the foundations, local oversteepening of slopes, porous layers etc. The generic case of low FOS slopes is addressed here but the full range of site specific weaknesses is outwith the scope of this study. It may be the case that existing low factors of safety are already a function of saturation and increased rainfall may not make this worse (unless the infiltration capacity is not yet taken up).

It is reasonable to state that a precise analysis of the impact of future rainfall on embankment stability would be difficult to present. The approach therefore has been to discuss easily understood boundary conditions and to examine dam performance and likelihood of occurrence in these terms. This gives a feel for the problem.

The main thrust of this commentary is in relation to rainfall effects. However, there are other climatic variables that can influence stability. Some of these are directly relevant to the rainfall scenario i.e. winds and temperature, while others are perhaps destabilising effects in their own right i.e. frost and snow.

Frost in the UK is generally accepted to be limited, at worst, to the immediate surface layer, not exceeding 500 mm depth. While severe frosts can cause heave of the soil, thus loosening and weakening the layer, this is generally limited to topsoil layers.

The effect of significant snow depths on a slope has both a loading and saturation impact. The loading impact might be regarded as moderately detrimental as it could increase the driving force of instability on a potential slip surface. Depending on whether the underlying slope is frozen or not, a slow melt of significant snow depth may saturate the surface layer more severely than the equivalent rainfall depth as run-off would be limited. However, it seems unlikely that the overall effect could be worse than normal wet periods of UK weather.

Desiccation (or shrinkage cracks) in highly plastic fills could perhaps be a more significant effect on stability through direct rainfall penetration and increased surface saturation depth.

2. Engineering Assessment

a) General

This section provides a discussion of dam embankment destabilising mechanisms.

The stability of an embankment will not reduce unless there is either an increase in load or a decrease in strength. For an existing dam, loads are essentially capped. There are however two mechanisms by which the strength can decrease; material degradation and increased pore pressures. Rainfall can influence both processes but it is assumed that, if vulnerable to degradation, fill material would already be undergoing the degradation due to present rainfall. Thus it is the impact of rainfall on pore pressures (and hence effective strength) that will be considered here.

Dams are designed to retain water long term as a design feature and this imposes a certain pore pressure regime on them to which they are resistant. (Not all other embankments have this capacity - roads, flood banks, railways etc). They are also subjected to wave carry over and wind blown spray as well as direct precipitation. In some circumstances they are tolerant of overtopping. At first consideration these factors might suggest that more intense rainfall will not create conditions worse than these design cases.

While high groundwater levels in the abutments and foundations are also potentially detrimental they are considered less significant. Generally speaking dams are less likely to be sensitive to groundwater variations due to climate change as the existing presence of the reservoir is the dominant influence on groundwater in the abutment zone. Saturation at the toe of a dam could also be significant but in most UK embankment dams this is either the present case or, in more modern designs, drainage provision would prevent saturation.

The concern here is that rainfall infiltrates the crest and downstream slope of a dam creating a vertical seepage regime with associated pore pressures, and that increased rainfall may amplify these effects thus decreasing stability.

Persistent long-term rain might be expected to have a more severe impact on infiltration pore pressure than short intense rainstorms. This will be a function of slope steepness and degree of run-off together with the receptiveness of the embankment fill to percolation/absorption as well as surface drainage provision.

Once a dam is saturated there is little else that additional rainfall can do other than cause surface erosion. The cases to be considered are therefore pore pressure build up in downstream shells as a result of more prolonged, heavier rainfall, plus the potential for surface erosion under extreme rainfall events.

b) Saturation Mechanisms

Soil/water interaction within an embankment dam - When built, the fill making up an embankment dam will have a fairly consistent moisture content that (together with the compactive effort applied) will initially determine the density of the fill and hence its strength. This includes the tendency for heavily compacted high moisture content, cohesive materials to generate construction pore pressures, which reduce strength.

In time these pore pressures will dissipate. Consolidation of the embankment fill will also take place over time and strength will increase. However, very plastic fills can swell and create suction in the voids rather than pore pressures. In a moist atmosphere the unimpounded embankment dam might remain in a soil/moisture equilibrium almost indefinitely. In very hot, dry climates an embankment could progressively lose moisture content or even desiccate, gaining strength but losing flexibility and perhaps impermeability.

However, for a dam embankment in service in a temperate maritime climate such as the UK there would be a zone of surface saturation through infiltration in addition to the internally saturated zone due to the seepage regime set up by the reservoir head (defined broadly by the phreatic surface). Depending on permeabilities and drainage there may be a zone within the downstream shoulder with no pore pressures, although capillary action can fully saturate some shells.

Seepage (and hence pore pressure distribution) is influenced by drainage boundaries, in that changes of zone permeability and the internal geometry affect the way in which void water enters or leaves a zone under seepage or consolidation.

Many of the pore pressure influencing parameters are difficult to predict e.g. permeability. The boundaries between fully and partially saturated zones are also varied by weather conditions.

There are some dams, which as a function of their permeability and material type allied to their location in regional climate terms, may be prone to increases in the pore pressure within the body of the downstream shoulder.

In general it is assumed that, with homogeneous fill zones in embankments and therefore constant infiltration permeability of the downstream shoulder, infiltration pore pressures are zero or very small. However, one class of embankment whose integrity may be susceptible to increased pore pressure and hence reduced stability is that where the permeability of the shoulder decreases with increasing confining pressure. Those susceptible to this effect are the dams where the shoulder is composed of material with a value permeability less than 10^{-8} m/sec and there is an effective basal drainage, i.e. flow is vertical. The permeability of the shoulder fill therefore decreases with increasing depth and there is potential for excess pore pressures to build. As quoted by P.R.Vaughan in the 34th Rankine lecture, the permeability could decrease by up to 2 orders of magnitude.

The effect of this could be significant if climate change results in increased rainfall duration and if the net surface infiltration increases while the transmisivity at depth remains limited. This could lead to significant pore pressures, which in turn would reduce the operational strength and hence reduce the stability of the embankment. This is the main class of embankment requiring consideration.

However, in order for this mechanism to have a detrimental effect as a result of climate change it is necessary for the infiltration rate to increase. The effective infiltration rate is a function of the slope angle, material properties and surface treatment as well as the rainfall intensity itself. With a permeability value less than 10^{-8} m/sec, the maximum infiltration of a typical embankment is likely to be 500mm/annum.

In areas where the effective infiltration is currently at the maximum value there would be no increase due to greater rainfall and pore pressures would not change. In areas where the effective infiltration is currently less than the maximum there could be an increase in infiltration and hence pore pressures, due to increased rainfall.

The key question then is whether climate change can influence the stability of embankment dam slopes and this is related to the way in which surface infiltration can affect the stability of a slope.

Surface saturation is a balance of evapotranspiration/infiltration/drainage (and in the UK is normally regarded as a net gain to saturation). What then are the limiting influences of surface induced saturation – do fully saturated conditions approach the pore pressure regime produced by rapid draw down conditions on the upstream slope of a dam, and would full saturation require constant rain?

The conditions necessary to develop full saturation of a downstream shell (clay) are continuous long-term exposure of the surface to excess moisture (no surface drying) with no drainage above foundation level.

c) Stability Concerns

In relation to slope stability the concerns are that the foundation is weak, or the fill is weak, or both. This determines the type of slope failure

For existing dams the underlying strength of the foundation and fill is established (once drained) as determined by construction. However this is influenced by the presence of excess water inducing pore pressures and thus reducing the effective strength.
Surface softening may also occur (due to swelling).

The downstream shells of UK dams are normally partially saturated. If they were to become fully saturated then the pore pressure regime would approach (but not exceed) that applying to the upstream slope during rapid draw-down.

Stability would be judged by the least favourable combination of pore pressures and failure surface. Normally this results in either shallow surface slips or deep-seated slips having the lowest factor of safety. Superficial (surface) slips are not the major concern here. It is deep-seated slips that represent the real risk to embankment dam safety.

Stability decreases if loads increase or strengths decrease. In the context of climate change impact on downstream shoulders, a greater zone of saturation would marginally increase the load through dead weight and could also reduce the strength through increased pore pressures at depth, or softening at the surface.

What types of embankment (configuration/nature) are vulnerable – Strong cohesive fills with steep slopes might have a beneficial combination of run-off and impermeability such that increased rainfall would not increase saturation. Weaker and more permeable cohesive fills, particularly with flatter slopes may be more receptive to pore pressure build up from surface infiltration. Shoulders of non-cohesive material would accept greater infiltration but would also drain better and be less sensitive to pore pressure build up although seismic loads could be a concern with fine grained material.

Embankments constructed of material liable to swell and create suctions are a potential problem. Local failures can occur in the years following construction as surface fluctuations in saturation affect pore-pressure equilibrium. The material has to be of moderate plasticity and placed dry to induce swelling and suctions. Saturated, low-plasticity fills that have reached pore pressure equilibrium are not a major problem. If the dam is more than 10 years old and there has been no evidence of localised slips then the problem may not exist.

d) Typical UK Embankment Dam Types

It is necessary to consider the variation in downstream shell construction and geometry of the dominant types of UK embankment dams in order to relate the specific performance characteristics of these to the perceived problem.

Thus we need to consider the response of several key dam configurations based on their equilibrium pore pressure regime and the potential for changes.

i.e. homogeneous, puddle core and zoned forms as basic cases plus the following potential additional features:

+toe drainage
+drainage blanket
+core drainage
+slope drainage

e) Performance

Winter/Summer cycles influence near surface strengths of original ground. Stiff clays are particularly vulnerable. Dam slopes can exhibit similar performance. Seepage boundary conditions are also important.

Winter pore pressures can approach hydrostatic values in embankment slopes up to a depth of approximately 2 m but decrease dramatically in the summer. This seasonal variation gradually reduces up to about a depth of 4 m at which point pore pressures become directly proportional to depth (although always less than hydrostatic).

However this assumes that the slopes are fully saturated and that the vertical permeability profile permits free movement of this water. Consideration has to be given to whether the flow moves downslope or is affected by underlying drainage. If there is preferential horizontal permeability then this is important

Do we have any indication of how typical dams might behave if fully saturated. Perhaps the simple answer to this is to look at the performance of upstream shoulders under the action of rapid draw-down conditions. This leads to conclusions on stability.

Superficial upstream slope stability on rapid drawdown is influenced by the presence of face protection which in some cases provides a free draining, high strength layer giving a confining pressure to the soils below. Downstream slopes rarely if ever in the UK have such a layer.

Deep-seated stability is a function of material strength and slope geometry for given pore pressure situations (and assuming strong foundations). Downstream slopes on any UK embankment dam are likely to be similar in basic material strength to the upstream shell but to be slightly steeper sloped (unless weak foundations are the dominating influence on slope design)

A vigorous growth of grass on a level area of heavy cohesive soil in intermittent light rain conditions will probably prevent the saturation of the soil. Heavy rain in dull conditions would change this situation to one of almost continuous saturation. Increasing slopes will vary the outcome between these extremes.

Well-cropped grass is believed to perform better than long grass in limiting surface saturation and, erosion considerations apart, both are considerably better than unprotected fill.

The overall detrimental effect must be a function of how often and for how long the surface is kept saturated i.e. has a film of water formed on the surface. This would be enhanced if the film of water increased to a finite depth (thus creating pressure at the interface) or by preventing the water from running off. The scale of input can be expressed as a table of light and heavy rainfall on varying slopes showing the likely effect on saturation and erosion.

Table 2.1 - For the case of cohesive soils in a UK climate

	Saturation	Erosion
Steep slopes, bare		
Light rain	limited	low
Heavy rain	seasonal	high
Moderate slopes, grassed		
Light rain	none	zero
Heavy rain	seasonal	low
Gentle slopes, grassed		
Light rain	seasonal	zero
Heavy rain	established at depth	low
Flat ground		
Light rain	established at depth	zero
Heavy rain	total	low

All of these will vary with soil type, underlying drainage, preceding weather conditions/soil moisture and wind speed/temperature/humidity

In these terms continuous sub-surface drainage blankets are not helpful to the process as they tend to hold moisture against the surface of the structural fill having drained the topsoil layer quickly but reducing the potential for evaporation and transpiration. On the other hand herringbone drains are believed to assist the overall drainage process without the moisture holding disadvantages attributed to blankets. However this is a subject on which opinions differ and the opposite effect is sometimes argued.

f) Summary of Geotechnical Response

The typical UK embankment dam is a moderate section of cohesive material (1:3 upstream, 1:2.5 downstream, in one or two zones) with a central clay core. Slopes are almost exclusively grassed. The extent of drainage varies considerably but most of the stock will have little or no formal slope drainage. Occasionally embankments have surface or sub-surface drains either as a part of the initial design or to improve very wet slopes, but these features are limited. There will also be some embankments with permeable shells.

Dams are unlike other embankments from two main perspectives:

- 1. They retain water and are thus partially saturated by design
- 2. They have design features to deal with water, both internally and externally.

For a homogeneous dam the body is almost fully saturated and pore pressures exist within the body of the dam. The downstream face may be only partially saturated although drainage provision, rainfall and the nature of the fill will have an influence on this.

Upstream slopes are potentially vulnerable, under draw down of the reservoir, to high residual pore pressures and downstream slopes can be weakened by emerging seepage as well as pore pressures.

Modern dams have less of a pore pressure problem due to the design of effective cores and drainage features, which combine to reduce the saturated zone within the downstream shoulder.

Rainfall or wave carry over can in the cases described above, cause saturation of the downstream shell. The extent to which this happens is a function of the frequency and duration of the event exposing the slopes to water as well as to the steepness of the slope and the properties of the fill.

In most modern dams the upstream shoulder will remain stable even after rapid draw down of the reservoir. Upstream slopes are generally flatter than downstream slopes for this reason thus a fully saturated d/s shoulder will be less stable (usually) than a rapidly drawn down upstream shoulder.

3. Hydrological Assessment

This section provides a commentary on the climatic features of the UK relevant to the perceived embankment instability problem.

The main hydro-climatic features of interest to this problem are point rainfall intensities, storm rainfall depths, seasonal rainfall depths, rainfall frequency, and evaporative losses. The following text briefly describes the characteristics of these in the present climate and how these are projected to change in the future.

a) Current UK Climate/Regional Variations

Prevailing south-westerly air flows give Britain its generally mild wet climate. On a regional scale this establishes the “normal“ precipitation pattern of wetter in the north and west, drier in the south and east (Figure 3.1). The mean annual precipitation range for Britain is approximately 600mm to 3500mm. The same regional pattern is also apparent in the spatial distributions of average seasonal precipitation: the example of Autumn is given in Figure 3.2. Figures 3.1 and 3.2 also show the mean wet-day frequency as a percentage of days. Again distinct regional variation exists (the characteristics of which are broadly similar in all seasons) with areas in the north west experiencing wet days for more than 85% of the year and conversely areas in the south east having wet days for less than 40% of the year. The two figures also give an indication of the inter-annual variability, which in some periods suggest regional fluctuations spanning multiple years. Generally annual precipitation depth anomalies of plus or minus 20% can be expected relatively frequently whilst more extreme values of plus or minus 40% are not without precedent.

Estimates of extreme rainfall also vary significantly with location. The Flood Estimation Handbook (Faulkner, 1999) suggests that 100-year 1 day rainfalls range from 70mm to 200mm with the maxima occurring in the western upland regions, whilst 100-year 1 hour rainfalls range from 23mm in eastern Scotland to 55mm in some areas of southern England.

It should be noted that although the prevailing air flow is from the south west, it is not the only influence and there are alternative airflow patterns that can vary rainfall distribution and extreme rainfall characteristics. The weather associated with these airflows is summarised by O’Hare and Sweeny (1993) as follows.

Table 3.1: General weather characteristics and air masses associated with Lamb’s primary airflow types over the British Isles (from: O’Hare and Sweeney, 1993).

Primary type	Weather description
1. Westerly	Unsettled weather with variable wind directions as depressions cross the country, giving most rain in northern and western districts, with brighter weather in the south and east. Mild in winter with frequent gales; cool and cloudy in summer.
2. Northerly	In winter the weather is cold with snow and sleet showers especially along the east coast: blizzards may accompany deep polar lows. In summer the weather is cool and showery especially along the east coast.
3. North-westerly	In winter, cool showery changeable conditions with strong winds. The weather in summer is cool with showers on windward coasts; southern Britain may be bright and dry.
4. Easterly	Cold in the winter period, sometimes with severe weather in the south and east with snow and sleet, but fine in the west and north. Warm in summer with dry weather especially in the west; occasionally thundery.
5. Southerly	Warm and thundery in summer. In winter it may be associated with a low in the Atlantic giving mild, damp weather especially in the south-west, or with a high over central Europe, in which case the weather is cold and dry.

6. Cyclonic	Rainy, unsettled conditions over most of the country, often accompanied by gales and thunderstorms. Wind direction and strength is variable. Conditions normally mild in autumn and early winter, cool or cold in spring and summer and cool in late winter.
7. Anticyclonic	Mainly dry with light winds; warm in summer with occasional thunderstorms; cold often with frosts and fog in winter especially in the autumn.

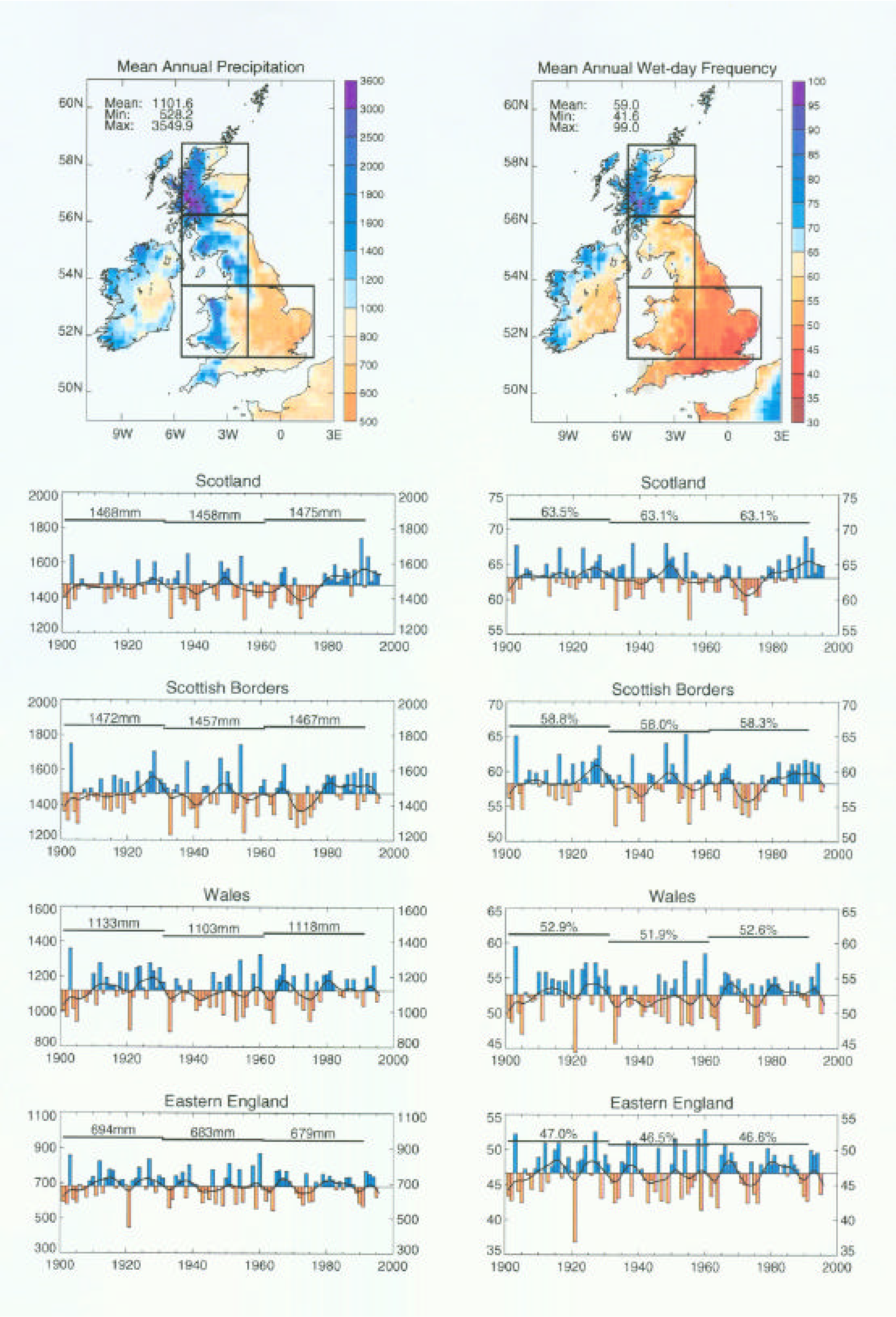

Figure 3.1 Annual precipitation and wet-day frequency (mm and percent, respectively). Time series are expressed as anomalies relative to the 1961-1990 mean. Horizontal bars represent the 1901-1930, 1931-1960 and 1961-1990 means respectively. (Reproduced from the UKCIP98 CD-ROM, by permission of the Climate Research Unit, Norwich).

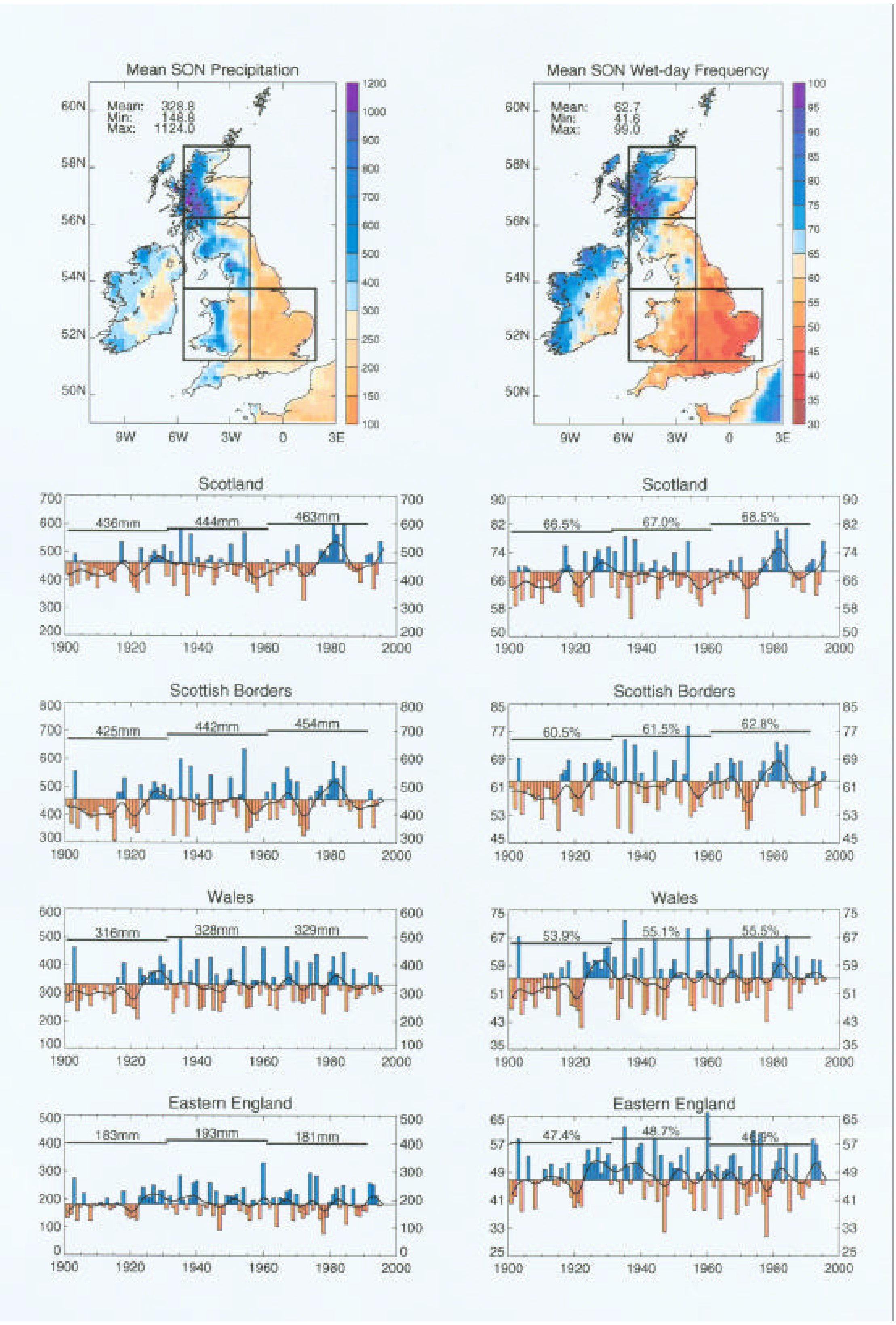

Figure 3.2 Autumn (Sep-Nov) precipitation and wet-day frequency (mm and percent, respectively). Time series are expressed as anomalies relative to the 1961-1990 mean. Horizontal bars represent the 1901-1930, 1931-1960 and 1961-1990 means respectively. (Reproduced from the UKCIP98 CD-ROM, by permission of the Climate Research Unit, Norwich).

The classes in Table 3.1 indicate that the causative conditions of precipitation can vary significantly across the country from accepted generalisations due to different synoptic circumstances. The airflow/system will influence the type of precipitation (frontal, convective etc) and this in turn has an impact on depth/intensity. This influences the occurrence of extended periods of heavy rain over a wide area as well as very localised extreme rainfall.

In addition to precipitation the other potentially important climate variable is evaporation[1]. This is a function of net radiation, temperature, humidity and wind speed. Mean annual potential evaporation (E_T) is a relatively conservative value across Britain. Values range from about 400mm in upland areas to a maximum of little over 600mm in more southerly and exposed coastal regions. Potential evaporation peaks during the summer and falls to almost zero during the middle of winter.

b) Comparison with monsoon climates

Perhaps the most obvious rainfall comparison by which to benchmark the UK situation and against which dam embankment performance can be judged is that due to monsoon conditions.

By comparison with the predicted climate changes the differences between UK rainfall and monsoon events are dramatic. While "instantaneous" intensities (mm/min) can be similar, the UK thunderstorm will last only a matter of minutes at that rate against periods of hours extending over weeks for the monsoon storm.

c) Projected changes due to global warming

The UKCIP98 scientific report (Hulme and Jenkins, 1998) currently provides the most authoritative and readily available guidance on projected climate change for the twenty first century for the whole of Britain. The report summarises the findings of the projected climate scenarios by suggesting:

"Changes in mean annual precipitation are quite modest. By the 2080s, annual precipitation increases by between 0 and 10 % over England and Wales and between 5 and 20% over Scotland. There are large seasonal differences however: winters and autumns become wetter over the whole UK, by up to 20 % for some scenarios. Spring, and especially summer, experiences a contrast between the south-east of the country which gets drier and the north-west gets wetter. Reductions in summer precipitation over large parts of England reach 10 to 20% by the 2080s. The year-to-year variability in precipitation increases almost everywhere even in seasons and regions when mean precipitation amounts fall".

"Potential evapotranspiration increases in all seasons, by the greatest relative amount in autumn and by the smallest in spring. By the 2080s, summer potential evapotranspiration over southern England is 10 to 20% higher than at present".

"Changes in mean climate will also be accompanied by changes in the frequency of extreme events. Intense daily precipitation events become more frequent, especially in winter, but there is little change in the return periods for daily-mean wind extremes. Changes in storminess are also 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".

"The natural variability of the UK climate is large, especially for variables such as precipitation and wind speed. This makes it difficult to attach high levels of significance to all of the

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[1] Potential evaporation is an indices of how much evaporation could occur if constraints related to the availability of water are not present. Actual evaporation (or actual evapo-transpiration) will principally be a function of this and depend upon both the type of vegetation cover and soil, and the antecedent soil moisture conditions. E_T is the most commonly used indices: defined as the potential evaporation from an infinite cover of short grass that does not have its water supply constrained.

changes in these variables that result from anthropogenic forcing. Analysis of natural climate variability on 30-year time-scales, shows that mean winter and summer precipitation varies by as much as +/- 10%, without any human forcing of the climate system".

An appreciation of the associated uncertainties inherent within these projections is important since inappropriate conclusions can easily be reached that the accuracy of the data cannot substantiate. In Table 3.2 a number of the variables are ranked subjectively by the authors of the UKCIP98 report in decreasing order of confidence. This indicates that some aspects of future climate are thought to be better described by the modelled scenarios than others.

Table 3.2 List of climate and associated variables, ranked subjectively by the authors of the UKCIP98 report in descending order of confidence. ('Regional' means the pattern of change across a country like the UK. THC – thermohaline circulation of ocean water, WAIS – West Antarctic Ice Sheet).

Climatic variable	**Level of confidence**
Atmospheric CO_2 concentration Global-mean sea-level Global-mean temperature Regional seasonal temperature Regional temperature extremes Regional seasonal precipitation Regional cloud cover Regional potential evapotranspiration	High confidence
Changes in climatic variability eg daily precipitation regimes	Low confidence
Climatic surprises (eg THC collapse and WAIS disintegration)	Very low or unknown

The UKCIP98 projections are due to be superseded by the UKCIP01 climate change projections in late 2001\early 2002. This may result in improved confidences. At the regional scale some work with the objective of better projecting changes in event rainfall characteristics has been conducted subsequent to the publication of UKCIP98. For example, initial provisional findings of research (Gregory, 2000), undertaken by The Met Office focused upon the Severn and Trent region, suggest that extreme daily rainfall depths (5-year to 20-year events) may increase by about 30% by the 2080s. Using a regional climate change model Hulme et al (2001) suggest that 2-year daily rainfalls in Scotland may increase by between 4% and 10% per $1^{o}C$ global warming. For the scenarios presented in the UKCIP98 report this equates to a range of increases between about 5% and 30%. However the authors stress that these projections need to be treated with caution as considerable uncertainty persists. The size of these recently published projected changes compare well with the surrogate values used in the main "Climate Change Impacts on the safety of British Reservoirs" report (Section 4). The approach adopted in the main report was to use the projected changes in average monthly precipitation as a surrogate for detailed event based estimates to provide a crude guide as to what may happen to the extreme design rainfalls used in reservoir safety flood studies.

Work to date on how climate change may affect storm event rainfall characteristics is still in its infancy and considerable uncertainties are event. Not least is how climate change may in the future influence the characteristics of British daily airflow types (such as those listed in Table 3.1), which largely determine the conditions and extent of extreme rainfalls.

Increases in summer potential evapotranspiration are suggested to be greatest in southern England – rising by between 10% and 20% by the 2080s. Equivalent increases are projected to be much smaller in the north with increases in Scotland only being between 0 and 10%. Autumn increases are projected to be greater with southern England projected to have 25% to 35% increases and Scotland to have 10% to 15% increases by the 2080s. However these larger autumn percentage increases have to be balanced against the lower amounts of potential evaporation that occur. In quantitative terms the increased depth of potential evaporation is about the same during the summer and autumn. The combination of greater summer evaporation and lower rainfalls in the south is likely to lead to more persistent soil moisture deficits, though the size of maximum deficits are not likely to significantly change since these are controlled by both vegetation and soil types. In the wetter northern regions summer rainfall is not projected to change by much and average soil moisture conditions will be unlikely to change by much (Price and McInally, 2001).

The above comments refer to average future conditions. Another climate change projection is that greater year-to-year annual and seasonal variability is likely to occur. This could affect the likelihood of extremes in ground wetness. However insufficient quantitative information is provided to allow the importance of this issue to be readily assessed.

In summary, available climate change guidance suggests that no part of the UK is likely to be dramatically wetter or drier on average by the end of the twenty first century, and nor will the seasonal nature of rainfall patterns change significantly. The larger regional seasonal increases are suggested to be of the order of 20%, whilst reductions are of the order of 10 to 20%. Quantitatively potential evaporation is likely to appreciably increase in the summer and autumn. This in combination with summer reductions in rainfall could lead to more persistent soil moisture deficits most particularly in southern Britain, though the size of maximum deficits are not likely to significantly change. Little guidance on how extreme rainfalls will change is available. What is available suggests that storm event depths might increase by up to 40% by the end of the century. However, the natural variability of the UK climate is large and extremes may not be easily discernible over the next 50 years.

d) Recent UK extreme rainfall events

There were a number of intense rainfall events in the UK in the last few months of 2000. The impact of these has in many cases been dramatic producing a number of "living memory" extremes and attracting considerable media speculation on the influence of climate change on these. A number of the more notable rainfall records from this period have been analysed using the Flood Estimation Handbook (FEH) (Faulkner, 1999) to determine the rarity of the events. Three of the worst affected areas were targeted – south east England, the headwaters of the River Severn, and Yorkshire. The detailed findings of this analysis are given in Appendix A. Table 3.3 summarises the general findings. The rarest events by duration from a selection of sites in each region are given to provide an indication of the severity of the conditions experienced.

Table 3.3 Summary of rarest rainfall events for differing durations identified in each of the three targeted regions for the period September – December 2000.

Region	Maximum return period of rainfall depth by duration (Units – Years)			
	1 day	4 day	16 day	3 month[**]
South east England	180	550	150	>>200
Yorkshire	2	100	400	>>200
River Severn headwaters	5	10	140	90

** Value based on regional analysis given in the November version of the Hydrological Summary for the United Kingdom (NERC, 2000).

However, it is instructive to recognise the scale of some historic events. Table 3.4 lists some of the more extreme events identified in the Flood Studies Report Vol 2 (NERC, 1975) together with the addition of event rarity as assessed on the FEH scale.

Table 3.4 Example historic heavy rain events in the UK. (Rarity assessed using the FEH DDF rainfall analysis software)

1/ The storm of 11th July 1932, Cranwell, Lincs (126 mm in 2 hours) Return period - 2003 years.
2/ The storm of 8th June 1957, Camelford, Cornwall (at least 138 mm in 2.5 hours) Return period - 1766 years.
3/ The storm of 4th August 1938, Torquay region, Devon (152 mm in 5 hours) Return period - 2277 years.
4/ The storm of 28th June 1917, Bruton region, Somerset (200 mm in about 8 hours) Return period - 5005 years.
5/ The storm of 18th July 1955, Weymouth region, Dorset (280 mm in about 15 hours) Return period - 12,650 years.
6/ The storm of 15th September 1968, south-east England (190mm in about 20 hours) The event at Barcombe in October 2000, was 175 mm in approx. 70 hours which was assigned a return period of c. 400 years. This event in 1968 appears even more extreme. Return period for this event at Barcombe - 1556 years. Return period for this event at London -1815 years (centre of storm was over London).
7/ The storm of 26th August 1912, Norfolk (210 mm in 24 hours) Return period at Norwich - 3306 years.
8/ The storm of 2nd/3rd November 1931, western Britain (up to 244 mm in 2 days) South Wales and Cumbria experienced highest total rainfalls. Return period at Pontypridd - 391 years.
9/ The storm of 20th-23rd July 1930, North Yorkshire Moors (304 mm in 4 days) Return period at just north of Pickering - 8084 years.

The rarity of these relatively short duration, historic storms are suggested to have been much more dramatic than the Autumn 2000 events. In this context the rarity of the individual Autumn 2000 events were severe but not without precedent when viewed in the national context. However it should be noted that the rainfall sequences of 2000 were notable for being spread over relatively large areas of the country. It should also be noted that the 3-month regional totals were almost without precedent in many parts of England and Wales with only November 1929 - January 1930 producing a higher 3-month rainfall total in the last 200 years (NERC, 2000).

e) Design flood events

In dam safety terms the most significant event is the design flood for spillway capacity/freeboard adequacy. This is often associated with a probable maximum precipitation on the catchment, albeit an areally adjusted figure for the catchment rather than a point rainfall. These events tend to be of shorter duration than the notable extremes of Autumn 2000. However, it is a useful benchmark to compare the 24-hour Estimated Maximum Precipitation[2] values to those rainfalls recorded in the areas most affected by the Autumn 2000 floods. Figure 3.3 shows how the recorded maximum daily values (adjusted for discretisation) compare to the local 24-hour EMP values. In these terms the 1-day events represent only 15 - 50% or less of the EMP. Thus for a small catchment at least the rainfall necessary to generate a probable maximum flood would have a much greater impact locally than the most intense of the Autumn 2000 storms. However, some of the historic short duration floods in Table 3.4 may be closer to EMP values.

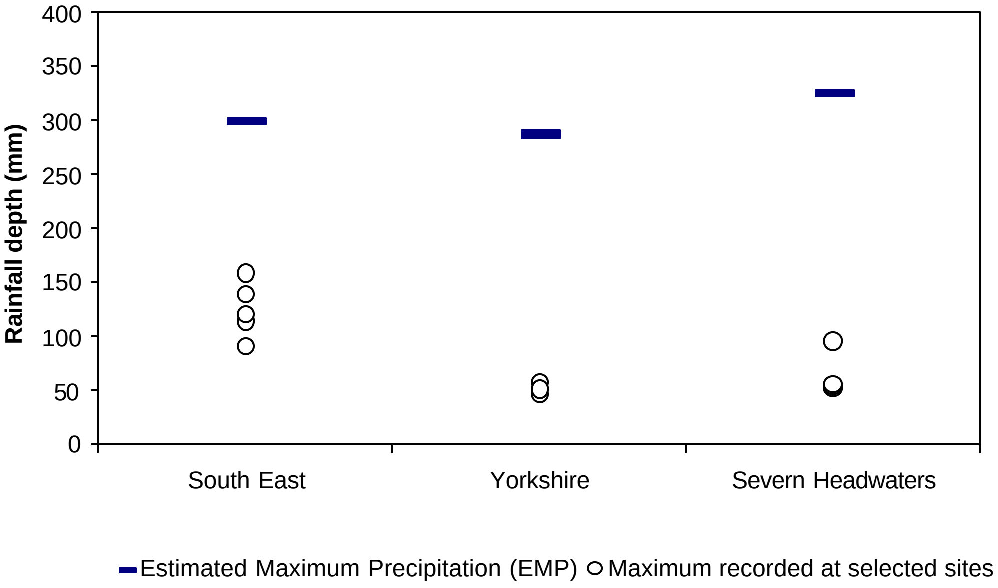

Figure 3.3 Comparison of Estimated Maximum Precipitation to maximum recorded rainfall depths for three badly affected regions from the period September – December 2000.

f) Summary

British precipitation is characterised by large spatial variation and appreciable inter-annual variability. Steep annual and seasonal precipitation gradients exist across the country with the wettest areas being on average about 5 times wetter than the driest locations. Inter-annual regional variability of plus or minus 40% is not without precedent.

Similarly short duration extreme rainfall estimates also show significant spatial variation with some areas likely to receive average intensities that can be two to three times that which would be expected for the same rarity in other locations.

Conversely evaporation is a much more spatially conservative variable which only shows limited inter-annual variation.

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[2] Estimated Maximum Precipitation (EMP) – an estimation of the maximum possible rainfall that could feasibly fall at a specified location. EMP estimates taken from the Flood Studies Report Vol 2.

In the context of world-wide rainfall the British rainfall characteristics are not considered extreme.

Projected climate change scenarios for the UK suggest that changes in average annual precipitation will be relatively modest, with the largest regional increases being only 20% for the 2080s time horizon. Average seasonal changes are projected to span a range of plus and minus 20% by the 2080s with winters and autumns in the north received the greatest increases and the summers in the south east suffering the greatest decreases. How changing climate might affect the typical weather types that give rise to extreme UK events is still relatively poorly understood. However tentative projections suggest that short duration extreme rainfall depths might increase by up to about 40% by the end of the twenty first century.

Although climate change projections suggest that increases of up to 20% to 40% to rainfall depth characteristics might be likely by the end of the twenty first century, such increases will for most locations not extend the range of present UK precipitation characteristics. However, where such increases occur at locations currently possessing the most extreme present rainfall characteristics then the expected range of UK precipitation characteristics is likely to be extended, though not dramatically.

Potential evaporation is likely to appreciably increase in the summer and autumn. This in combination with summer reductions in rainfall could lead to more persistent soil moisture deficits most particularly in southern Britain, though the size of maximum deficits are not likely to significantly change.

Recent short-duration extreme rainfalls (September – December 2000), taken from three of the worst hit regions of Britain were not unprecedented when set within the context of UK-wide historic records. One-day maxima from the three regions for this period only represented at most about half of the estimated maximum precipitation possible. The 3-month rainfall totals for many of the regions in England and Wales may be more notable particularly as the rainfalls were so extensive, yet even these are not unprecedented with higher 3-month totals depths recorded in 1929/30.

4. Overall likelihood of problem occurring

Rainfall induced effects on embankments are erosion, surface slips and deep-seated slips. At the present time there is little evidence that these present a problem to UK embankment dams. However, if there were a potential problem, then we might expect to see it reflected first in the wetter NW of the country. To give that some scale we might also expect to see evidence of more serious problems world-wide, where monsoon climates in particular might represent the worst that could happen.

This suggests that lack of evidence has to be related to superior performance of certain dam types and that we should consider whether the most vulnerable of UK embankments are not presently subjected to national or international extremes

It is likely to be the nature of the embankment material rather than changes in rainfall that determine the deep-seated stability of UK embankment dams. This is due to UK climate providing net infiltration year on year and establishing a soil/water equilibrium. This will be unaffected by increases in rainfall, certainly those predicted by climate change.

Surface (or superficial) stability may however be sensitive to increased rainfall in the sense that the top 2 m of any embankment could remain fully saturated for longer, although there will still be a distinct summer/winter cycle of wetting and drying. However, as the most adverse surface pore-water pressure regime is presently experienced annually then any stability problems due to climate change are unlikely.

If the above discussion deals with the way in which an embankment responds to rainfall and in particular the scale of event that can have an impact then the next step is to consider the likelihood of such events occurring.

What are the conditions that could make UK dams more vulnerable to increased rainfall that dams world-wide are not?

This needs to approach the degree of saturation applied to upstream slopes and infers that a climate of almost constant heavy rain would be required.

Wave overtopping magnitudes can be more severe than rainfall intensity/duration and the threshold of overtopping causing damage is rarely approached.

From a geotechnical design point of view there may be little effective difference between a clay embankment dam in East Anglia and a similar dam in Argyll despite a factor of 2-3 in rainfall terms.

Similarly there is no significant design difference in the use of cohesive fills between UK embankment dams and world-wide dams subjected to wet tropical climates (other than the use of local material).

Normally the most significant design feature related to climate is the downstream face protection. Where the climate precludes the use of grass then stone is normally used to prevent erosion. It is perhaps less clear how the use of stone rather than grass will affect the saturation of the fill surface and the evaporation from this surface.

Dams world-wide withstand a wide range of rainfalls yet show little design variation for the fill types closest to those common in the UK (cohesive).

In countries where rainfall is more intense than the UK (Monsoon Countries) the problems might have been expected to manifest themselves already. Our experience (Nigeria, Pakistan etc) has shown that surface erosion rather than pore-pressure is likely to be the problem where rainfall intensities are high. However, this only becomes a concern where soils are exposed due to drought conditions.

Dam design and construction in the UK is not notably regional in climatic terms and the same type of dam is as likely to found in a dry area as in a wet area. Thus the performance of dams in the exposed NW of Scotland might offer a clue as to performance under wetter conditions of a dam in SE England.

Possible special cases are sand fill dams such as Colliford and very flat sloped weak clay embankments such as Alton and Ardingly. The sand fill might be expected to drain freely irrespective of rainfall and rate of infiltration with little or no impact on effective strength of the material beyond that already allowed for from current extreme rainfall. The flat clay sloped embankments common in the SE of England are often a function of weak underlying clays requiring reduced embankment loadings rather than inherent weakness of the shoulder material itself and thus these slopes will have an in-built margin of strength.

The most vulnerable type of dam is perhaps one of sandy/silt where absorption is relatively high yet drainage is poor. Much will depend on the stress induced permeability reductions within the shoulder of such embankments to determine whether pore pressures will build up and further, whether increased rainfall will amplify this phenomenon.

Surface erosion – this is not a problem provided the embankment is adequately grassed and maintained (as is the case with most UK embankments).

Groundwater – there may be some impact on abutment stability and on foundation stability through saturation of the toe although most UK embankments, other than new construction, are already saturated in this area.

Unless the bank material is particularly receptive to infiltration then the difference between normal rain saturating the surface of a slope and very heavy rain doing likewise is reflected in the amount of run-off and the resulting erosion potential.

Saturation and pore pressure build up is a reflection of the ability of the material to absorb moisture as well as the availability of moisture.

One of the biggest dangers might be during modifications to old embankments involving addition of fill zones above saturated surface layers.

There are perhaps 3 categories of extreme rainfall relevant to UK embankment dams.

Existing extremes known to occur from records of storm events
Potential changes due to climate change
The likely maximum point rainfall associated with a PMF catchment event

Dam embankments are currently prone to damage during extreme intensity rainfall events, sometimes this is associated with the attendant wind and wave action causing wave carry-over. More commonly it is related to poor run-off control from crest features or adjacent natural ground. (reference Combs Reservoir).

However, many well grassed embankments can tolerate solid overtopping water and the prospect of general rainfall alone replicating such an erosive impact is difficult to envisage.

Some embankments may become marginally stable due to saturation from heavy rainfall over prolonged periods but this is probably within the bounds of historical rainfall intensity and independent of climate change impacts as they are presently understood.

As with all aspects of reservoir safety, public protection is the main concern. The danger of instability in a dam embankment (even if it is only a superficial slip) is that it will cause a breach and associated release of substantial flows that could cause loss of life in communities downstream. Normally deep seated slips are the main concern such that the section of the dam is severely compromised and seepage through the reduced section can cause secondary (piping) failure, but shallow slips at crest level can also compromise integrity if they reduce freeboard.

5. Other types of earthwork structure where impact may be more significant

There are cases other than dams where the physical conditions could make increased rainfall a problem.

Road and railway embankments are constructed to quite different standards to those of dams and other non-water retaining formed embankments will be similar. All of these will be vulnerable to saturation through percolation and to ponding at the toe of the slopes. These fills may be less dense and more permeable than dam embankments with a greater potential for weakening through saturation.

The situation with railway and motorway cuttings might be regarded as very different where changes in rainfall intensity and increased long term averages might have an effect on groundwater levels and hence stability of these cut slopes.

Canal cutting slopes would be similarly affected but canal banks might be closer in some ways to the response of dam embankments although it is recognised that canal slopes generally have a marginal factor of safety under present operating conditions.

The slopes of landfills and other waste tips might also respond adversely to increases in groundwater levels if not direct rainfall.

Flood banks are a special case of water retaining structure and should perhaps be given separate consideration.

6. References

Geotechnical references

1. International conference on soil mechanics and foundation engineering, 9th, Tokyo, 1977. Vol 3, pp 411-413. Procs. Tokyo; Japanese Society of Soil Mechanics and Foundation Engineering, 1978.
2. Terzhaghi, K. & Peck, P.B. (1967) – Soil Mechanics in Engineering Practice, 2nd edition. New York: Wiley.
3. Vaughan, P. R. (1994). Geotechnique 44, No 4, 573-609 (34th Rankine Lecture)
4. Vaughan, P.R., Hight, D.W., Sodah, V.G. & Walbancke, H.J. (1978). Factors controlling the stability of clay fills in Britiain. In clay fills, pp. 205-218. London: Institution of Civil Engineers.
5. Vaughan, P.R. & Walbancke, H.J. (1975). The stability of cut and fill slopes in boulder clay. Proceedings of symposium on engineering behaviour of glacial materials, pp 209-219. Birmingham: Midland Society Soil Mechanics and Foundation Engineering

Hydrological References
Faulkner, D. (1999) Flood Estimation Handbook Vol 2: Rainfall frequency estimation. Institute of Hydrology, Wallingford.

Gregory, J. (2000) Climate change: Factors to consider in relation to coastal and inland flooding. In CIWEM conference proceedings: Flooding Risks and Reactions, 5 October 2000, London, 1-10.

Hulme, M. and Jenkins, G.J. (1998) Climate change scenarios for the UK: scientific report, UKCIP Technical Report No. 1, Climatic Research Unit, Norwich, 80pp.

Hulme, M., Crossley, J. and Xianfu, L. (2001) An exploration of regional climate change scenarios for Scotland. Report for The Scottish Executive Central Research Unit. Edinburgh, pp 41.

Institute of Hydrology (1968) Research 1968, 48 pp.

NERC (1975) Flood Studies Report Volume 2. Natural Environment Research Council, London.

NERC (2000) Hydrological summary for the United Kingdom: November 2000. CEH Wallingford, Wallingford, UK.

Price DJ & McInally G (2001) Climate change: Review of levels of protection offered by existing flood prevention schemes. Scottish Executive Central Research Unit (In press).

O'Hare, G. and Sweeney, J. (1993) Lamb's circulation types and British weather: An evaluation. Geography*,* 78: 43-60.

Wilson, E.M. (1974) Engineering Hydrology. Second Edition, MacMillan Press Ltd.

Appendix A: Analysis of September – December 2000 extreme rainfall

Introduction

There were a number of intense rainfall events in the UK in the last few months of 2000. The impact of these has in many cases been dramatic producing a number of "living memory" extremes and attracting considerable media speculation on the influence of climate change on these. A number of the more notable rainfall records from this period were obtained and analysed to determine the rarity of the events. Three of the worst affected areas were targeted – south-east England, the headwaters of the River Severn, and Yorkshire.

Rainfall data

The most notable rainfall records for a selection of gauges from each of the three regions were requested from the Environment Agency. Table A.1 lists the gauges for which data was provided.

Table A.1 Raingauge records analysed.

Region	Name of raingauge	Location	Grid reference
South east England	Barcombe	Nr Lewes	TQ 425 155
	Burnt Oak	Nr Crowborough	TQ 509 269
	Ringmer	Nr Lewes	TQ 448 128
	Waldron	Nr Uckfield	TQ 537 186
Yorkshire	Gouthwaite Reservior	Nr Harrogate	SE 139 681
	Lower Dunsforth	Nr Knaresborough	SE 435 643
	Eccup Reservoir	Nr Leeds	SE 309 422
Severn headwaters	Dolydd	Nr Llanidloes	SN 873 905
	Sarn	Nr Newtown	SO 206 906
	Welshpool	Welshpool	SJ 233 073
	Bishop's Castle	Nr Newtown	SO 338 873

Methodology

Daily rainfall data was provided. Maximum rainfall totals for a range of durations between and including 1 and 16[1] days were abstracted and the rarity of the events were estimated using the Flood Estimation Handbook depth-duration-frequency (DDF) model (Faulkner, 1999). In addition the regional rainfall return periods for the three month duration September – November were obtained from the "November 2000 - Hydrological Summary for the United Kingdom" (NERC, 2000). As such it is strictly not directly comparable to the individual raingauges estimates, but does, nevertheless, give an indication of the general rarity of the sequence of rainfall experienced.

Results

Figure A.1 shows the estimated return periods of the rainfall data as a function of duration for each of the regions. The regional estimates are indicated only broadly: reflecting the level of detail given in the November 2000 - Hydrological Summary for the United Kingdom.

The maximum rainfall depths for each of the three regions for different durations are plotted in Figure A.2. This sets the recently recorded depths in the context of maximum recorded rainfall envelopes derived for both the UK and the world (Institute of Hydrology, 1968). As can be seen the recent events do not closely approach either envelope, and are about an order of magnitude lower than the world envelope.

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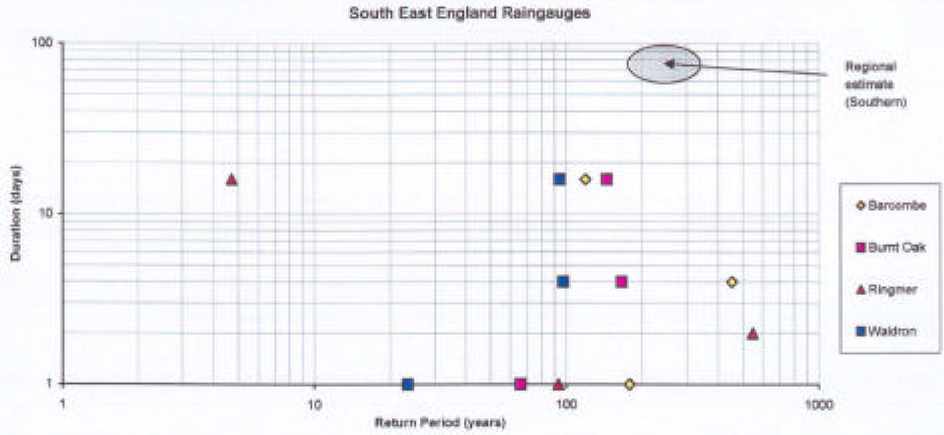
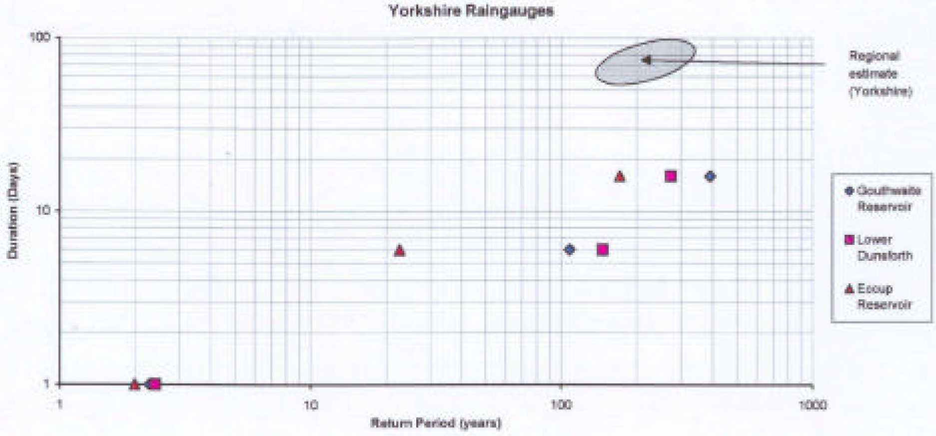
[1] The Flood Estimation Handbook DDF model is limited to a maximum duration of 16 days.

Figure A1 Analysis of the rarity of rainfall experienced during September – December 2000 for the three targeted regions.

Figure A2 Comparison of the most extreme rainfall depths recorded in the three targeted regions during the September – December 2000 period to the upper envelopes of recorded extreme rainfall in both the UK and the world.


South East England Raingauges


Yorkshire Raingauges

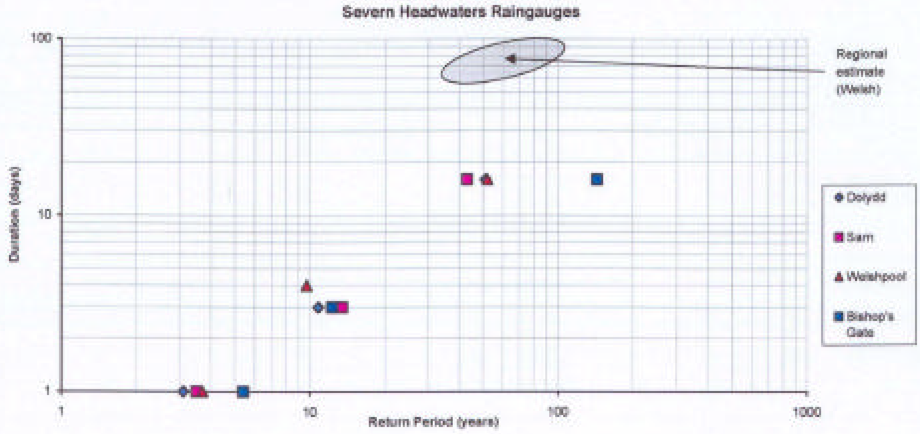

Severn Headwaters Raingauges

Figure A1: Analysis of the rarity of rainfall experienced during September - December 2000 for the three targeted areas

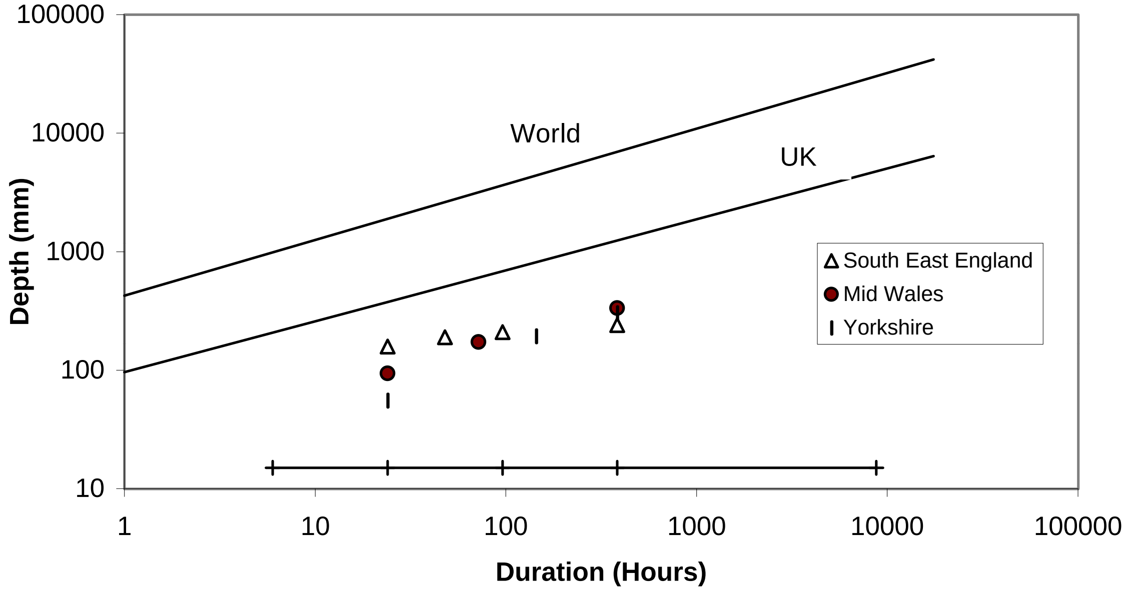


Figure A2: Comparison of the most extreme rainfall depths recorded in the three targeted regions during the September - December 2000 period to the upper envelopes of recorded extreme rainfall in both the UK and the world.