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A preliminary risk assessment of the potential for groundwater flooding during the winter of 2007/8

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Executive Summary

The unprecedented summer floods that took place in England during July 2007 have raised concerns about the prospects for flooding over the coming winter. Floods are essentially caused by exceptional rainfall but a series of antecedent conditions are generally prerequisites. These occur over a comparatively short period, ca. days, for fluvial floods but over a longer period, ca. months, for groundwater flooding. Therefore, considerable caution needs to be exercised regarding the potential for fluvial flooding this coming winter but it is possible to begin to consider the situation for groundwater flooding, where the prerequisites are dominantly the depth to the water table and the water content of the overlying soils.

Groundwater flooding is defined, in this report, as flooding that can be attributed to water originating beneath the ground surface from permeable strata through a natural process. The aim of this study is to determine the extent to which the exceptional summer rainfall in 2007 has increased the likelihood of groundwater-related and other flooding occurring , in parts of England and Wales, during winter 2007/08 . It is an initial risk assessment, i.e. Tier 1 – a qualitative screening process

The objectives are to:

- assess the situation of soil water and groundwater at the end of July for England and Wales using real data;
- make a preliminary assessment of possible trajectories of ground water levels, soil moistures and river flows (where baseflow is dominant) for the coming 6-8 months (using simple groundwater and rainfall-runoff models where available and appropriate);
- carry out an initial risk assessment to identify the flood risk (probability and consequences) for different possible rainfall scenarios and inform / forewarn;
- make recommendations for further detailed risk assessments (Tier 2 and 3) of any potential for groundwater flooding this coming winter, including the optimum timing of these.

Much of the knowledge about the occurrence of groundwater flooding is based on the winter of 2000/01, although data are available for more localised flooding that occurred in the winters of 1993/94, 1994/95 and 2002/03. Few incidences of groundwater flooding have been recorded for non-Chalk aquifers and so this report focuses on the outcrop of the Chalk aquifer.

The Chalk is particularly vulnerable to groundwater flooding due to the complexity of its hydraulic properties. These include: dual permeability through the matrix and fractures; low storage, low ability for water to flow in the saturated zone; significant variability in the hydraulic properties vertically and spatially. Even within the outcrop of the Chalk there is variability in the number of reported incidences of groundwater flooding so that the Chalk in Yorkshire and Lincolnshire has a low incidence of events compared to the Chalk to the south.

In the summer of 2007, there have been several very wet periods, resulting in unprecedented May-July rainfall totals across much of southern Britain. The heavy storms in June and July even resulted in significant potential recharge occurring in many areas. Groundwater levels responded to this recharge so that, in the Cotswolds and parts of the Chalk in Yorkshire and Lincolnshire, previous summer groundwater levels were exceeded. In the southern outcrop of

the Chalk, the response in the water table was more subdued but rises were observed at a number of sites. Complementary evidence is provided by the increased flow in streams and rivers sustained primarily by outflows from springs and rivers.

Remarkably, late July soil moisture deficits were lower than the average for the end of November across many aquifer outcrop areas. This extreme departure from the typical seasonal pattern implies that, in the absence of a very dry autumn, the 2007/08 recharge season could extend for more than twice the normal duration in much of the English Lowlands. Where late summer groundwater levels already exceed the seasonal average there will clearly be an enhanced risk of fluvial and groundwater flooding through the coming autumn and winter. Rivers with a strong baseflow component will be particularly at risk if significant fluvial flooding were also to occur. However, it should be noted that above average winter rainfall does not necessarily imply the occurrence of floods.

An initial assessment of the likelihood of groundwater flooding occurring over the winter of 2007/08 has been made; based on the status and past behaviour of groundwater level observation wells in selected areas of the chalk outcrop. It provides a useful indication of the level of risk although there is significant uncertainty about these predictions. The results suggest that there is an appreciable risk of high groundwater levels in the Chalk of Yorkshire and Lincolnshire, but the low number of reported incidents of groundwater flooding suggests that this may not be translated into flooding except locally. Significant flood events would be possible in most other areas if winter rainfall was high, although in the Southern Wessex Chalk the risk is lower. With average rainfall, the Berkshire and Chiltern Chalk could be subject to limited flooding; more extensive flooding may occur if there are periods of intense rainfall this winter.

It is recommended that the outcrop of the Chalk should be the main focus for further risk assessments. However, there is the possibility of localised events on other major aquifers this winter and, if they occur, they should be monitored so as to add to our knowledge of this phenomenon.

Currently, there is significant uncertainty about the risk of groundwater flooding on the Chalk aquifer this winter. This is dominantly due to:

- Uncertainty over the rainfall through the autumn, and thus the onset of the “recharge season”;
- Uncertainty as to the quantity and the spatial variability of potential recharge during this summer and its progress through the unsaturated zone;
- Uncertainties as to the amount and intensity of winter rainfall.

There is little that can be done about the last of these. The first and third can be addressed by a further assessment in mid-October. By then the onset of recharge is likely to have begun and the recharge during July is likely to have reached the saturated zone, thus giving greater confidence to an assessment of the conditions at the start of significant recharge occurring through the winter. It would also be appropriate at that time to make a more detailed assessment of conditions in the areas identified as being at risk and using more sophisticated methods to predict the likely occurrence of groundwater flooding.

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Introduction

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Groundwater flooding is defined, in this report, as flooding that can be attributed to water originating beneath the ground surface from permeable strata through a natural process. Groundwater flooding can also occur in other hydrogeological settings, for instance in river valleys where permeable superficial deposits are in hydraulic content with surface water, and flooding can occur as water moves from rivers into adjacent superficial deposits but these will only be touched on in passing.

The aim of this study is to determine the extent to which the exceptional summer rainfall in 2007 has increased the likelihood of groundwater-related flooding, and other flooding, occurring during winter 07/08, in parts of England and Wales. It is an initial risk assessment, i.e. Tier 1 – a qualitative screening process

The objectives are to:

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- make recommendations for further detailed risk assessments (Tier 2 and 3) of any potential for groundwater flooding this coming winter, including the optimum timing of these.

The occurrence of groundwater flooding

There is an appreciable amount of, mostly local and qualitative, evidence of historical groundwater flooding (British Hydrological Society - Chronology of British Hydrological Events) in the UK but, prior to the winter of 200/01, groundwater flooding had received relatively little formal attention from either academic or regulatory communities, because the events that had occurred in the previous few decades were localised. The 2000/01 event is probably the best formally documented event, although data are available for more localised flooding that occurred in the winters of 1993/94, 1994/95 and 2002/03. The 2000/01 flooding was largely due to the exceptional rainfall in the period between September 2000 and April 2001, the wettest 8-month sequence in the 241-year England and Wales rainfall series (Marsh and Dale, 2002); the rainfall anomalies were most outstanding across southern England. The steep recovery of groundwater levels, following the summer recession, began from levels that were at or a little above the seasonal mean. Water-table rises gathered momentum from mid-October and, during the late autumn the rates of rise were remarkable. In many areas the groundwater levels exceeded the previous maxima for several months. From early December, water tables began to reach the ground surface in many aquifer outcrop areas and groundwater flooding persisted for more than four months in some places. The meteorological conditions that led to the 2000/01 floods were focussed on southern Britain, with the greatest the impacts on the Chilterns, the Berkshire and Wessex Chalk, and on the Chalk of the South Downs. Jacobs (2004) collated data on the incidence of groundwater flooding during the three winters of 1994/95, 2000/01 and 2002/03. They concluded that groundwater flooding appeared to be largely restricted to the outcrop of the Chalk where there are no overlying impermeable deposits. Subsequently, Jacobs (2006a, b) extended this analysis, confirming this conclusion.

There is very little information on the occurrence of groundwater flooding in non-Chalk aquifers. Jacobs (2006a) attributed the low incidence of groundwater flooding outside the Chalk aquifers to one or more of:

- Relatively high storage values;
- Lower permeability formations having a slow rate of recharge;
- High permeability formations rapidly dissipate any elevated heads.

It is possible that groundwater flooding occurs more widely in these geological formations, but has not been formally recorded.

Given the widespread and extreme nature of the 2000/01 flooding and the low incidence of groundwater flooding that resulted in non-Chalk aquifers, the current analysis focuses on the Chalk.

The complexity of its hydraulic properties make the Chalk particularly vulnerable to groundwater flooding. The Chalk is considered to be a dual permeability system as flow occurs both through the pores of the matrix and through fractures distributed throughout the rock mass. Both the pores and the fractures have a low storage in the unsaturated zone. Thus recharge to the saturated zone results in comparatively large rises in the groundwater levels. Although the movement of water downwards in the unsaturated zone is dominantly through the matrix (Mathias *et al*., 2006, Ireson *et al*., 2006), and thus slow, the response of the water table occurs on a much shorter timescale due to the hydraulic pressure transmitted through the water in the matrix, which is close to saturation. In addition, a more rapid response can occur due to flow through the fractures when the water table is close (ca less than 5 m) to the ground surface. In the saturated zone, the flow of water is almost exclusively through the fracture system and so there is a relatively low ability for water to travel laterally through the system - thus elevated groundwater levels can take months to dissipate, increasing the impact of any flood.. In addition, the hydraulic properties vary vertically (e.g. Rushton *et al.* 1989, Bradford 2002, Williams *et al*., 2006) which can result in a non-linear response of groundwater levels. A further level of complexity is that the hydraulic properties vary spatially. Controls on the distribution of permeability and storage include lithology, structure and the effect of Palaeogene cover. Topography and periglacial processes can serve to enhance solution along fractures and hence permeability (Allen *et al*, 1997). This spatial heterogeneity explains much of the local variations in the occurrence of groundwater flooding recorded by Jacobs (2004). For instance the relatively high transmissivity of Chalk at outcrop in Lincolnshire and Yorkshire may allow faster drainage and thus the rapid attenuation of elevated groundwater levels, reducing the instances of flooding.

The areas most at risk from groundwater flooding in Southern England can be localised further. Jacobs (2004) identify that the Environment Agency Areas with the most reported occurrence of groundwater flooding from major aquifers are: Anglian – central; Southern – Hampshire & Isle of Wight; Thames – West and North East.

While the areas within Southern England affected by flooding in 200/01 are considered to be most at risk from future groundwater flooding, other areas of the Chalk, and other aquifers that might be susceptible to localised groundwater flooding can be identified from detailed geological mapping and groundwater level datasets. The lack of observational evidence from previous flooding episodes means that predicting the risk of future events in these areas is impractical.

Groundwater levels in the summer of 2007

Antecedent groundwater conditions

Following protracted drought conditions extending over two years, the seasonal recovery in groundwater levels in 2006 began from a very low base. Generally, the 2006/07 recharge season was initiated in the early autumn and the third wettest October-February period for England and Wales since 1960/61 ensured that groundwater levels in most major aquifer outcrops were above the seasonal average by early spring 2007. There were exceptions, including the very slow-responding Permo-Triassic sandstones of the Midlands. Modest March rainfall and a remarkably dry and warm April then triggered an early and relatively steep onset of the 2007 seasonal recession in groundwater levels.

Summer 2007

Synoptic patterns changed in early May – the strength, and southerly track, of the Jet Stream, together with elevated sea surface temperatures, contributed to a continuation of very unsettled, cyclonic weather conditions over the May-July period, especially across England and Wales. For this area, the three-month rainfall total eclipsed the previous May-July maximum (in a series from 1766) by an appreciable margin. Many wetter 3-month periods can be found but none since 1912 fall in the summer half-year (May-Sept). Across the majority of the major aquifer outcrop areas, the late May-July rainfall was more than twice the 1961-90 average, rising to over 300% in parts of the Cotswolds (Jurassic Limestone) and the Yorkshire and Lincolnshire Wolds (Chalk) – see Figure 1. Importantly however, rainfall anomalies were less outstanding across the South East (i.e. much of the area most vulnerable to groundwater flooding).

Within the May-July period there were several extremely wet episodes which generated substantial, and rare, summer recharge. The June rainfall total for Yorkshire was the highest for any month in a series from 1914 and exceptional storm totals were reported on the 15/16th and 24/25th – when Winestead (near Hull) recorded 100 mm in 12 hours. In July, a sub-tropical airmass stagnated over central England generating extreme rainfall totals: Pershore (Hereford and Worcestershire) recorded 145 mm in 25 hrs on the 19/20th (return period > 1000 yrs) with an area of around 3500 km^2 registering >100 mm (see Figure 2).

The unprecedented May-July rainfall across much of southern Britain produced hydrological conditions with no close modern parallel for the summer (June-August). An important measure of the singular nature of the 2007 summer is provided by the outstandingly wet soil conditions. At the end of June, MORECS[1] soil moisture deficits – averaged across England and Wales – were the lowest on record (in a series from 1961). End-of-July totals were similarly outstanding; substantially below the previous minimum for England and Wales (Figure 3). In a normal year, late-July soil moisture deficits are in the range of 90-110 mm across the major outcrop areas in the English Lowlands; deficits in 2007 were less than 30 mm over a very wide area (see Figure 4) and close to the water content at which flow occurs in a zone from the North York Moors to Dorset. This has important implications in relation to flood risk through the winter of 2007/08 (see below).

The groundwater response

Dry soil conditions normally preclude widespread aquifer recharge during the summer. In 2007, the very moist soil conditions resulted in the summer rainfall being very hydrologically effective in some areas. In parts of the Cotswolds, estimated infiltration in July exceeded the average for January (Anon. 2007). As a consequence, previous maximum summer groundwater levels were exceeded, by wide margins in some cases, e.g. at Ampney Crucis in the Jurassic Limestone of the Cotswolds. More notable was the unseasonably early recovery in the slower-responding Chalk of the Lincolnshire and Yorkshires Wolds (see Figure 5). In the latter, levels at Dalton Holme were the highest for the summer in a 120-year series. Exceptional summer responses also occurred in some western outcrops of the Chalk (e.g. at Rockley, Wiltshire). Generally, away from these – the wettest – outcrop areas, overall recharge through the summer remained modest, albeit often significant by comparison to the minimal recharge normally registered in the June-August timeframe.

Figure 6 shows the ranking of the July 2007 groundwater levels relative to previous July levels, for a network of index wells and boreholes across the country, illustrating the exceptional conditions. Particularly for the more responsive aquifer units, the ranking position is sensitive to the date of latest available level – those measured early in the month will not reflect the impact of the late-July rainfall. In addition, a number of factors (including the large spatial variation in rainfall, varying depth to the water-table, and differing aquifer characteristics) will also have influenced the scale and timing of the groundwater level response.

Complementary evidence of the magnitude of the groundwater replenishment during the summer is provided by the 2007 river flow patterns in streams and rivers sustained primarily by outflows from springs and seepages. Figure 7 shows 2000-07 daily flow hydrographs for a number of index rivers in England. The July peaks on the Evenlode, which drains from Cotswolds, and the Lambourn (Berkshire Downs) exceeded previous maxima[2] and by month-end baseflows (the groundwater contribution) were well above those in any previous summer. By contrast, flows in the Chess (Chilterns) and the Mimram (draining the Chalk, north of London) remained well within the normal summer range during July.

The spatial variation in fluvial baseflow response to the summer rainfall is paralleled by groundwater levels; in much of the South East, the July 2007 groundwater levels followed a

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[1] MORECS: Met Office Rainfall and Evaporation Calculation System (Hough and Jones, 1998)
[2] Note: in both cases it is assumed that the rainfall on the 19/20th July exceeded the infiltration capacity of the soils and surface runoff was a significant contributor to the highest daily flow).

reasonably typical recession. July levels were also within the normal late-summer range in many Permo-Triassic sandstones outcrops – although in a significant proportion of index sites in the Midlands levels are rising, a consequence of a characteristically slow recovery following drought conditions in 2004-06. Water currently descending through the unsaturated zone may be expected to produce further rises in the water-table during August (and later in some cases).

Historical perspective

Whilst very localised summer recharge, normally associated with convective storms, is not unusual, substantial and widespread aquifer recharge during the June-August period is very rare, particularly in the context of the last 100 years. Prior to the First World War summer half-year rainfall commonly exceeded that for the winter half-year (Nov-Apr) (Marsh et al, 2007) and summer infiltration was a more regular occurrence (e.g. in 1797, 1860, 1879 and 1912). Over the period during which a relatively dense borehole monitoring network has been maintained – the last 40 years – there is no summer recharge episode to compare with the hydrological conditions experience in 2007. Correspondingly, there are few analogues on which to base scenarios for the behaviour of groundwater through the coming autumn and winter. Fortunately, results from the recent NERC Lowland Catchment Research (LOCAR) Programme have substantially added to our understanding of the hydrological processes in the near surface, unsaturated and saturated zones of the Chalk with the result that we are better placed both to interpret the observations of the recent events and to make predictions of the future.

Groundwater outlook

Remarkably, late July soil moisture deficits were lower than the average for the end of November across many aquifer outcrop areas. This extreme departure from the typical seasonal pattern implies that, in the absence of a very dry autumn, the 2007/08 recharge season could extend across nine or ten months; more than twice the normal duration in much of the English Lowlands. Near-saturated soil conditions would allow the autumn and winter rainfall to be substantially more hydrologically effective than in an average year. Thus average rainfall from August to March may translate into 150% of average recharge across much of the Chalk outcrop, with greater anomalies in some areas. Where late summer groundwater levels already exceed the seasonal average there will clearly be an enhanced risk of fluvial and groundwater flooding through the coming autumn and winter. Rivers with a strong baseflow component will be particularly at risk if significant fluvial flooding were also to occur. However, it should be noted that above average winter rainfall does not necessarily imply the occurrence of floods. For example, last winter (October-March) the rainfall in England and Wales was significantly above average, 115-130 %, and yet floods were noticeable for their absence. This was because there were no exceptional rainfall events.

An initial assessment of the likelihood of groundwater flooding occurring over the winter of 2007/08 has been made based on the status and past behaviour of groundwater level observation wells in selected areas of the chalk outcrop. Three scenarios were examined.

A. High winter rainfall (>150% of long term average Oct – Mar)
B. Normal winter rainfall (100% of long term average Oct – Mar)
C. Low winter rainfall (75% of long term average Oct – Mar)

The historical data for the selected boreholes were then reviewed, and the average water level rise over winters with rainfall matching the selected scenario was calculated. The calculated water level rise was then applied to the current groundwater level, with some adjustments made to allow for further late summer recession. The resulting prediction was compared to the previous recorded maxima and to levels that are known to have produced groundwater flooding. Where predicted levels either exceed historical maxima or groundwater flooding trigger levels the risk is assessed as significant. Where levels equal historical maxima or flood levels the risk is assessed as possible, otherwise the risk of flooding is considered low.

The precision of theses analyses is very limited; there are no recent historical analogues for the intense July rains, so the precursors to historical floods will have been different. No account has been taken of rainfall intensity or its temporal distribution through the winter half-year. In a number of cases the predicted levels significantly exceed historically observed levels, but in reality non-linearity in borehole response to recharge and increases in spring discharge or baseflow are likely to limit the real rise in water table. A further source of uncertainty is that a significant amount of recharge from the July rains may not have reached the water table, leading to an underestimation of flood risk.

The results of the analysis are shown below:

Area	Borehole	Rise Flood risk	A - High	B- 100%	C - 75%
Yorkshire/Lincolnshire	Dalton Holme		9.504 Significant	8.25 Significant	6.03 Possible
	Aylsbey		7.56 Significant	7.26 Significant	4.41 Possible
Bekshire/Chilterns	Rockley		14.19 Significant	12.22 Possible	6.36 Low
Wessex	Compton		35.39 Possible	22.04 Low	12.67 Low
South Downs/Kent	West Dean No 3		2.59 Significant	1.21 Low	0.93 Low
East Anglia	Washpit Farm		6.38 Significant	3.79 Low	1.59 Low

These suggests that, in the Yorkshire/Lincolnshire Chalk, a significant groundwater event is likely even with average winter rains. Whether the predicted high groundwater levels will translate into groundwater flood events in this area is less clear, as few events have been previously recorded in the area. Significant flood events would be possible in most other areas if winter rainfall was high, although in the Southern Wessex Chalk the risk is lower.

With average rainfall the Berkshire and Chiltern Chalk could be subject to limited flooding, more extensive flooding may occur if there are periods of intense rainfall this winter, Figure 8.

At 75% of normal rainfall the figures suggest that the Yorkshire/Lincolnshire Chalk will still be close to long term maxima, and there would be a possibility of localised flooding.

Outside the Chalk, some areas of the Jurassic limestones and Permo-Triassic sandstones will have been subject to exceptional amounts of recharge. As discussed above, these aquifers are not considered to suffer groundwater flooding, but the possibility that flooding may occur, and that winter baseflows and spring discharges will be significantly higher than normal can not be dismissed.

The Met Office issued its forecast for Autumn 2007 on 23rd August (see Box 1). The outlook for temperature and rainfall could be beneficial in relation to the risk of groundwater flooding. Nonetheless, as the preliminary assessments have demonstrated, even rainfall well within the normal range could be associated with a significant flood risk in vulnerable areas. A more penetrating appraisal of the flood risk through the coming winter will be possible by October when the full impact of the summer rainfall will have registered at almost all index wells and boreholes, and there will be very limited further opportunity for significant soil moisture deficits to be maintained.

Recommendations

The historic occurrence of groundwater flooding suggests that these events are most likely to occur on the outcrop of the Chalk aquifer. Thus this should be the main focus for further risk assessments. However, there is the possibility of localised events on other major aquifers this winter and, if they occur, they should be monitored so as to add to our knowledge of this phenomenon.

Currently, there is significant uncertainty about the risk of groundwater flooding on the Chalk aquifer this winter. This is dominantly due to:

- Uncertainty over the rainfall through the autumn, and thus the onset of the “recharge season”;
- Uncertainty as to the quantity and the spatial variability of potential recharge during this summer and its progress through the unsaturated zone;
- Uncertainties as to the amount and intensity of winter rainfall.

There is little that can be done about the last of these. The first and third can be addressed by a further assessment in mid-October. By then the onset of recharge is likely to have begun and the recharge during July is likely to have reached the saturated zone, thus giving greater confidence to an assessment of the conditions at the start of significant recharge occurring through the winter. It would also be appropriate at that time to make a more detailed assessment of conditions in the areas identified as being at risk and using more sophisticated methods (see Calver 2000 for examples) to predict the likely occurrence of groundwater flooding, e.g. running models to investigate the level of precipitation that would trigger flooding for a given combination of initial soil water and groundwater conditions.

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Acknowledgments

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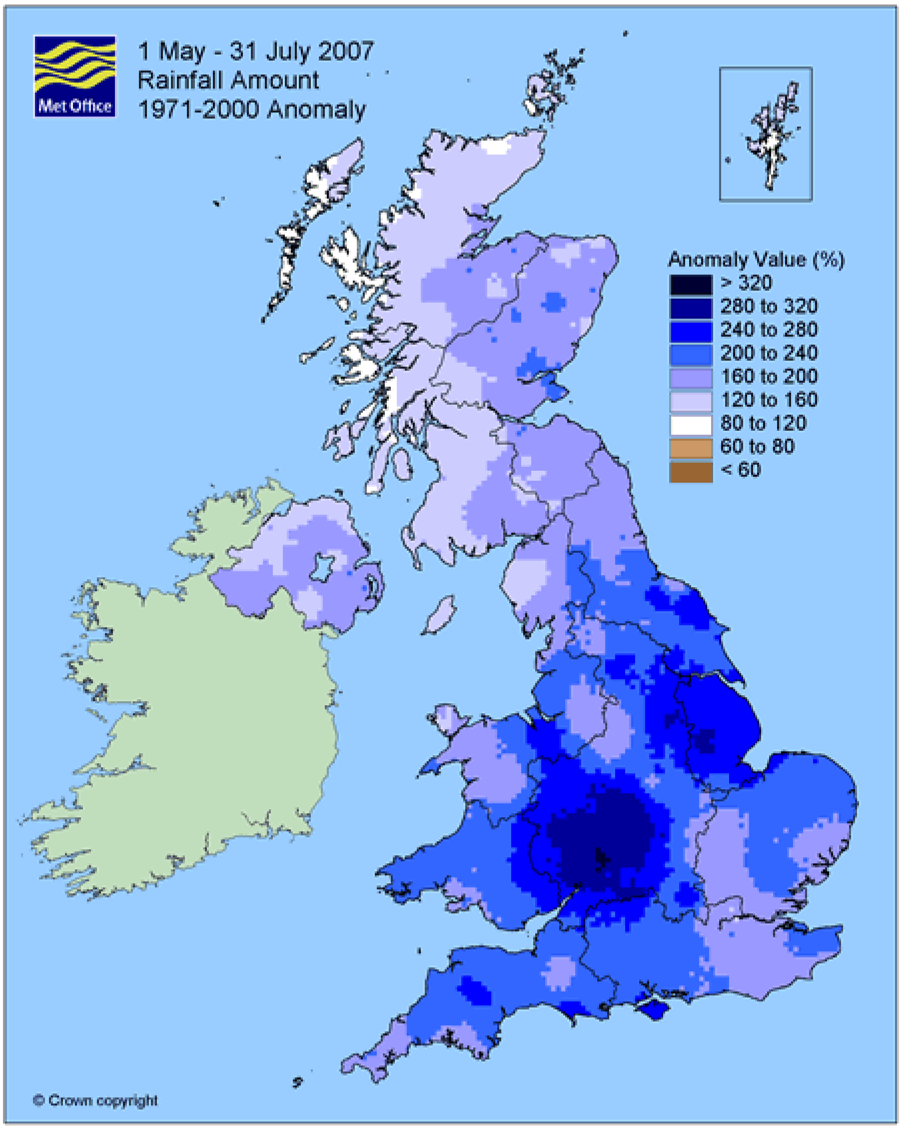

Figure 1 The rainfall anomaly (1971-2000) for 1 May – 31 July 2007 over the UK (reproduced courtesy of the Met. Office)

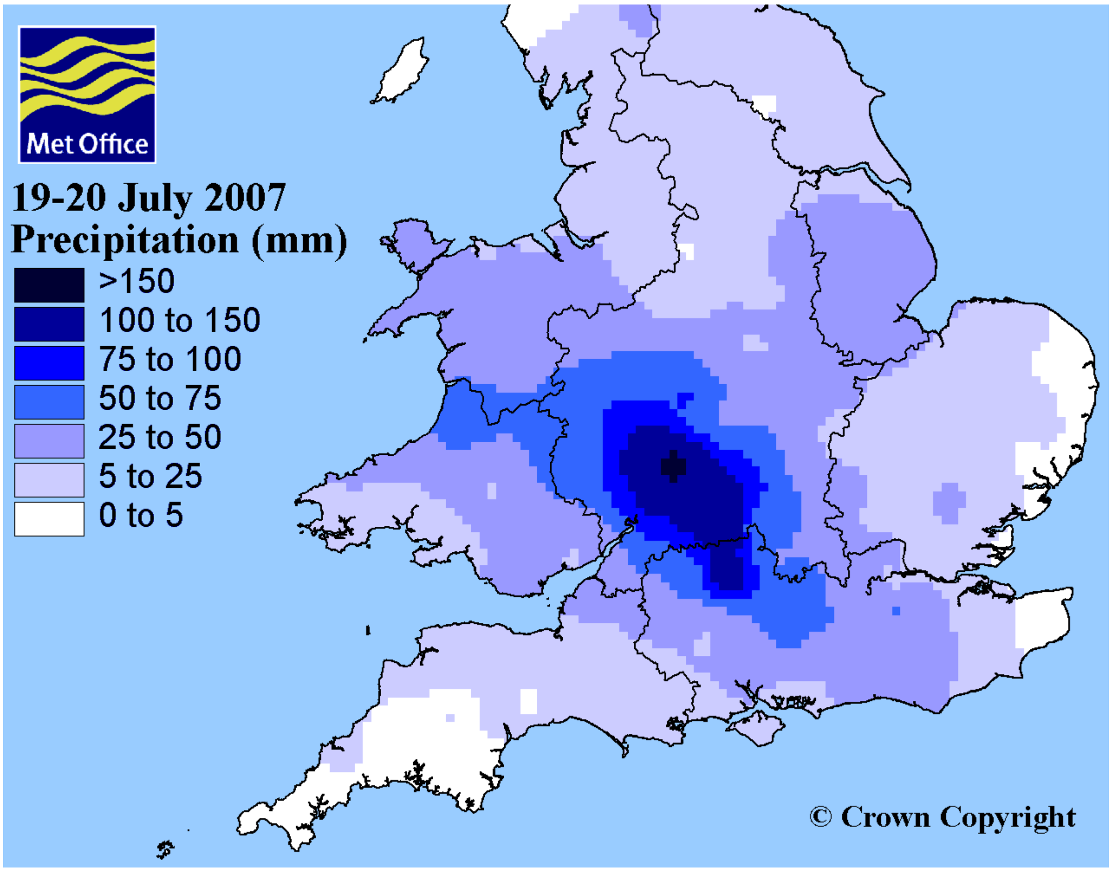

Figure 2 **The total precipitation for the period 19-20 July 2007 (reproduced courtesy of the Met. Office)**

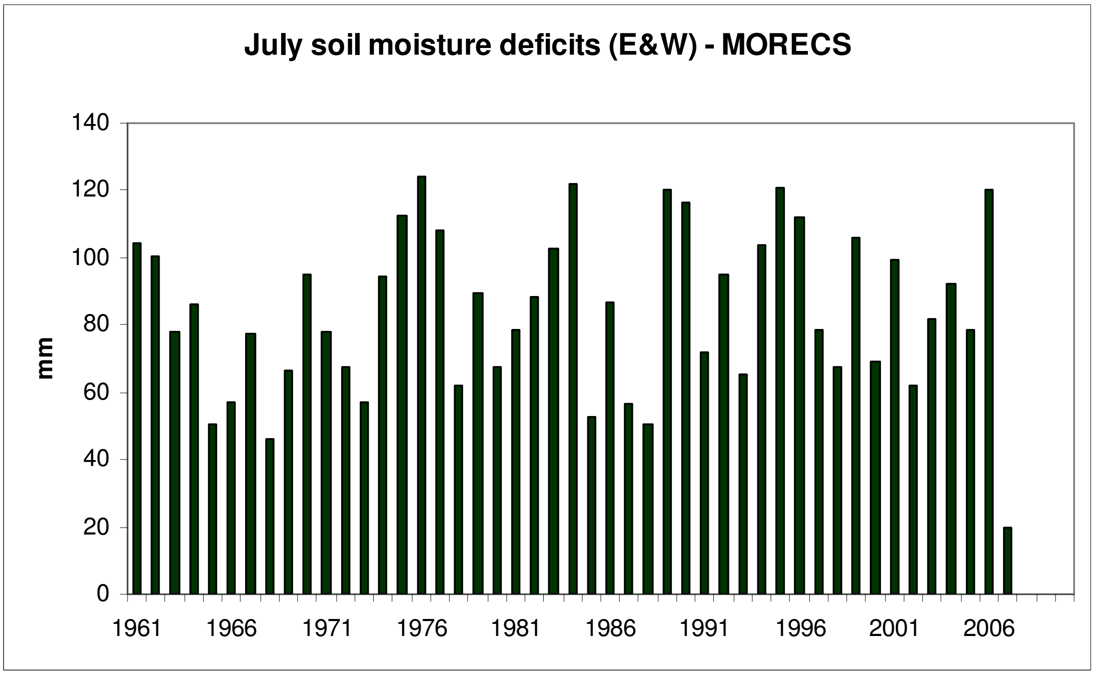

Figure 3 **Time series (1961-2007) of the July 2007 soil moisture deficits for England and Wales**

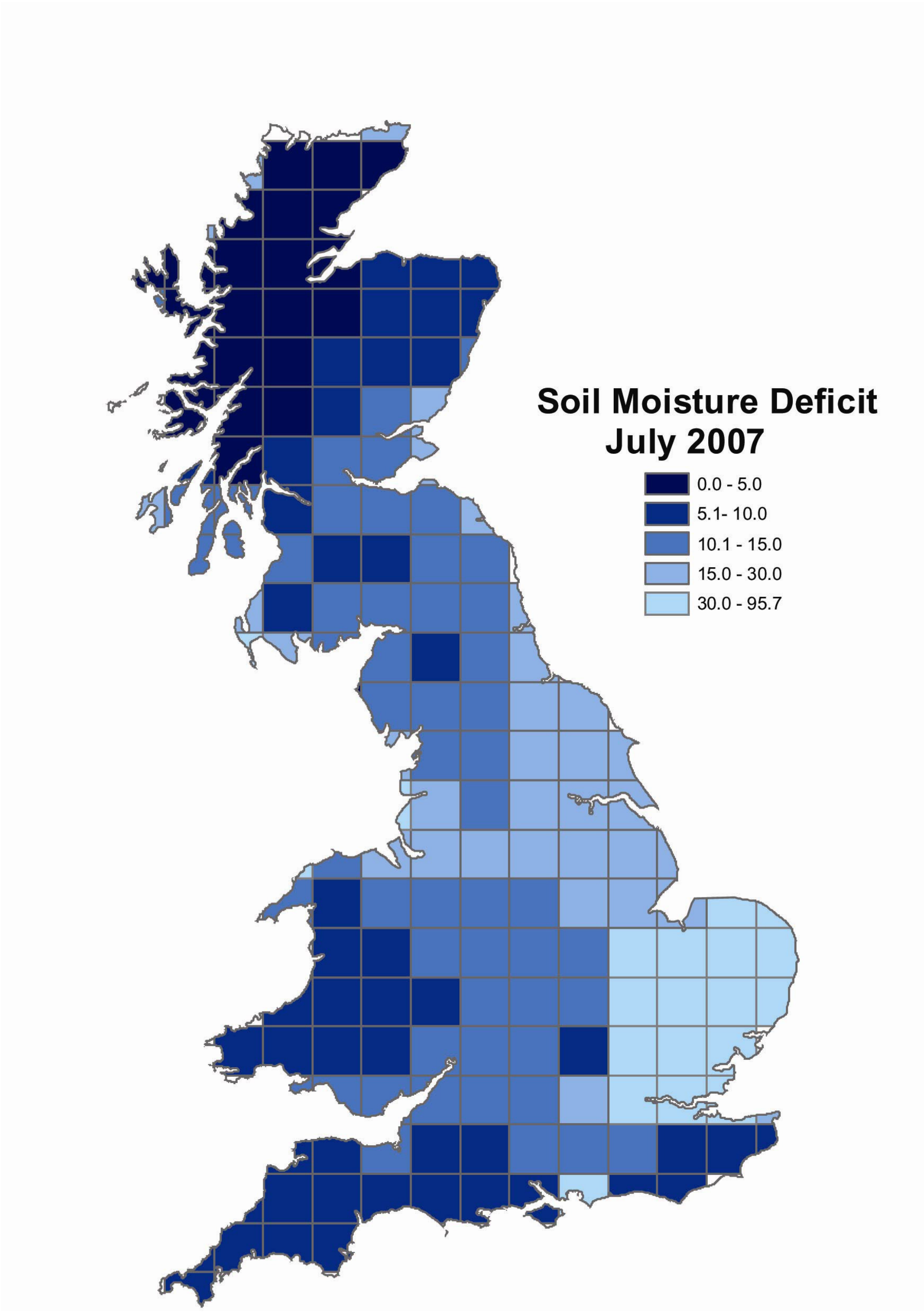

Figure 4 MORECS soil moisture deficits in late-July 2007

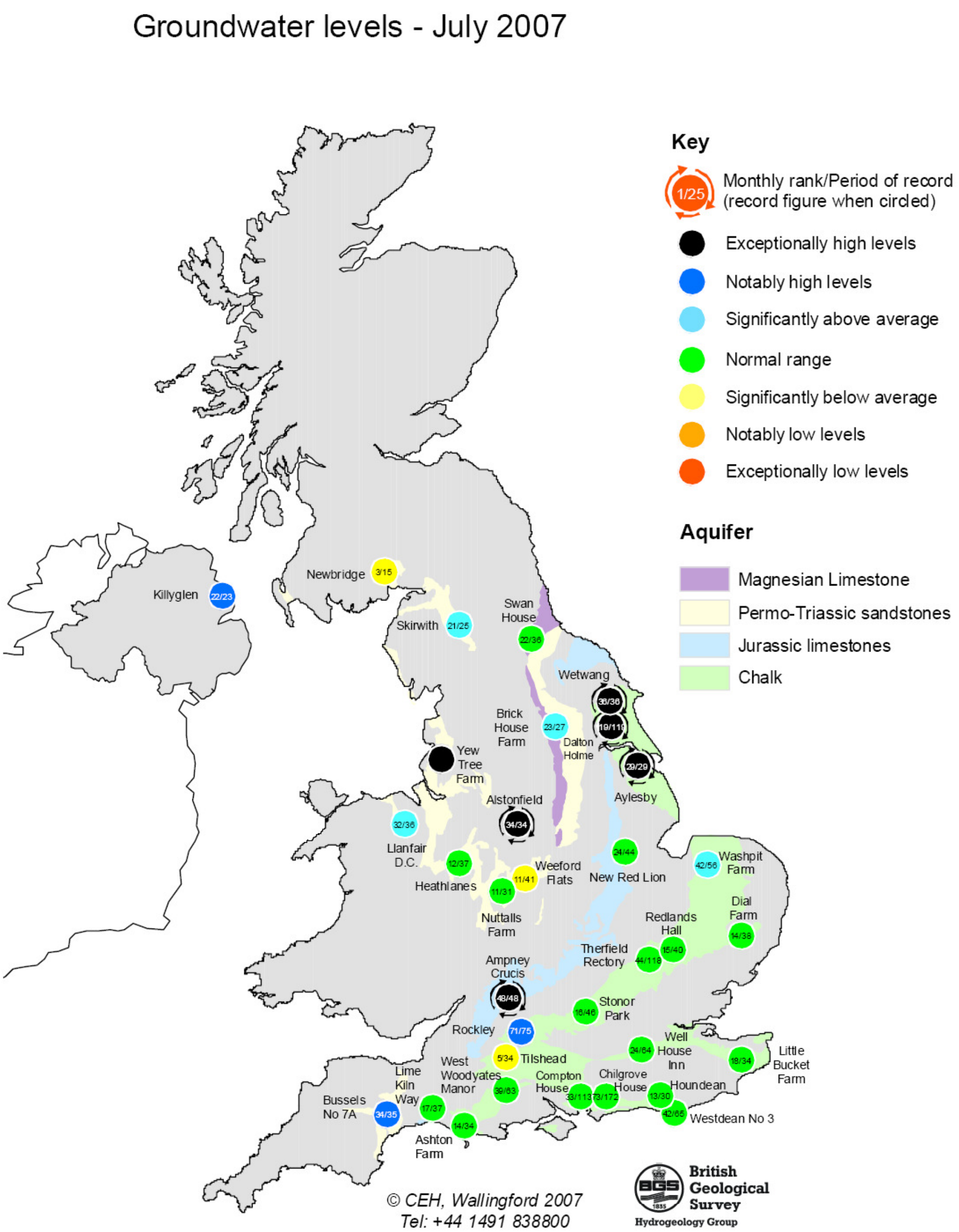

Figure 5 July 2007 groundwater levels

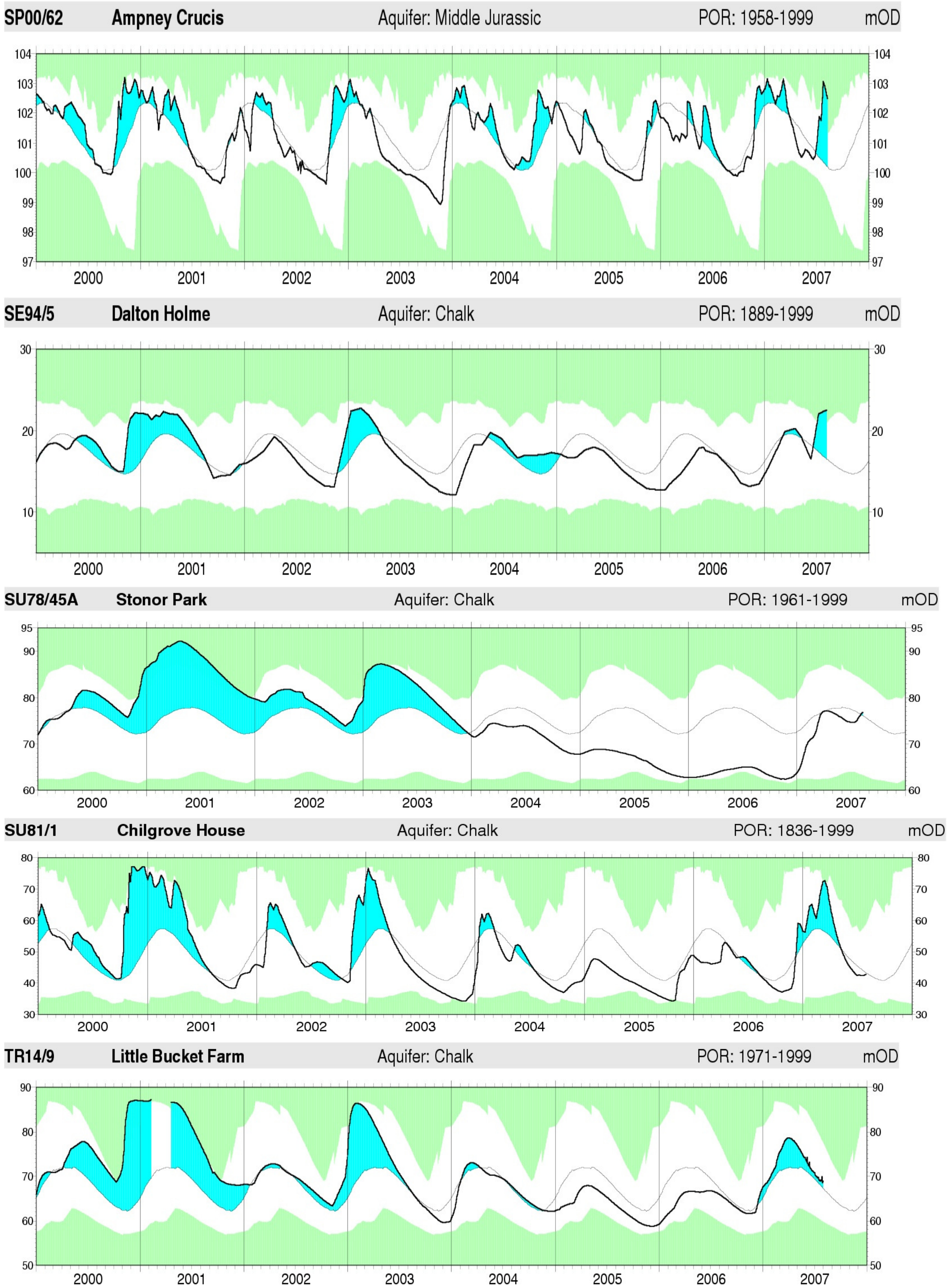

Figure 6 Ranking of the July 2007 groundwater levels relative to previous July levels for a series of index wells and boreholes

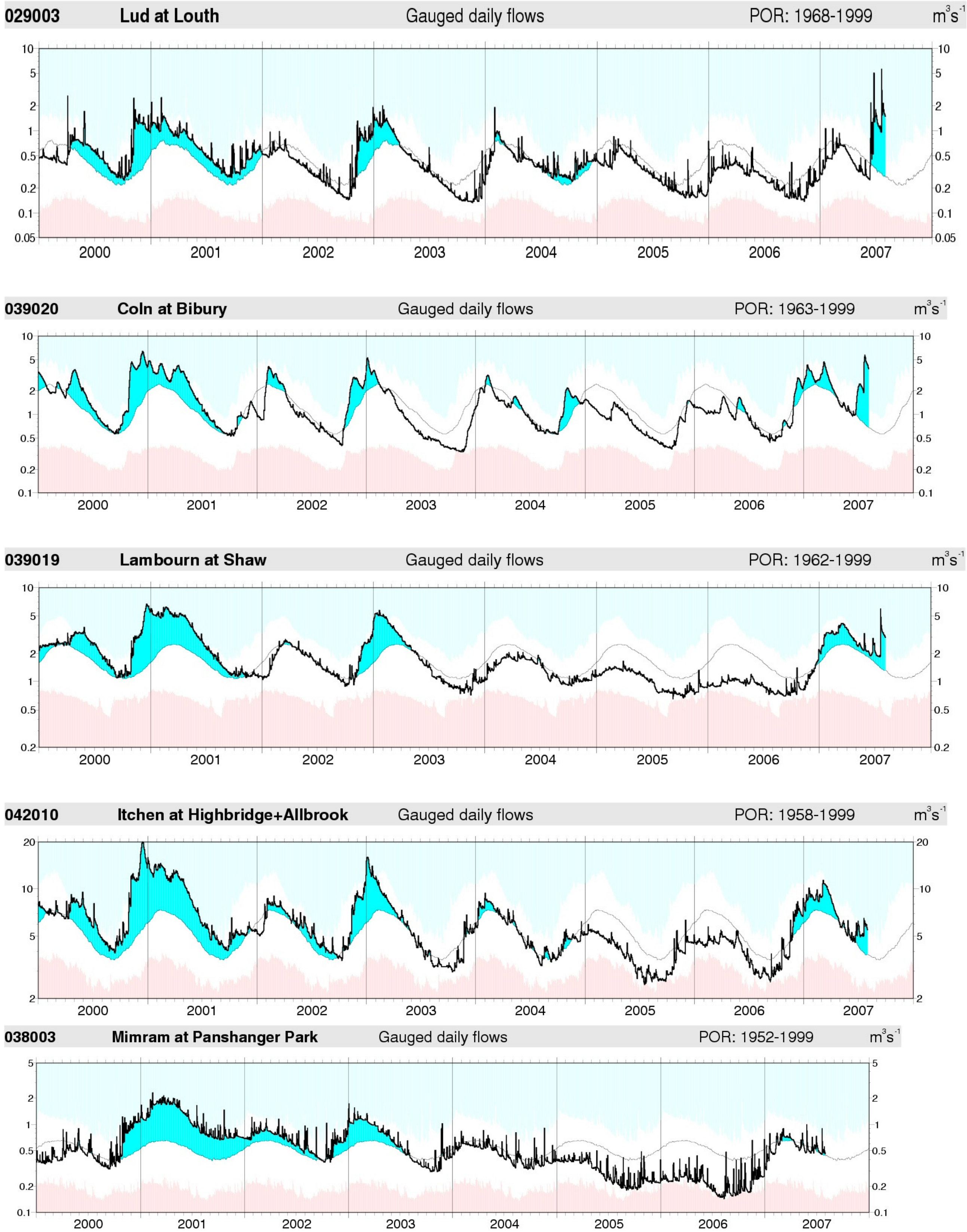

Figure 7 Daily flow hydrographs for a number of index rivers in England

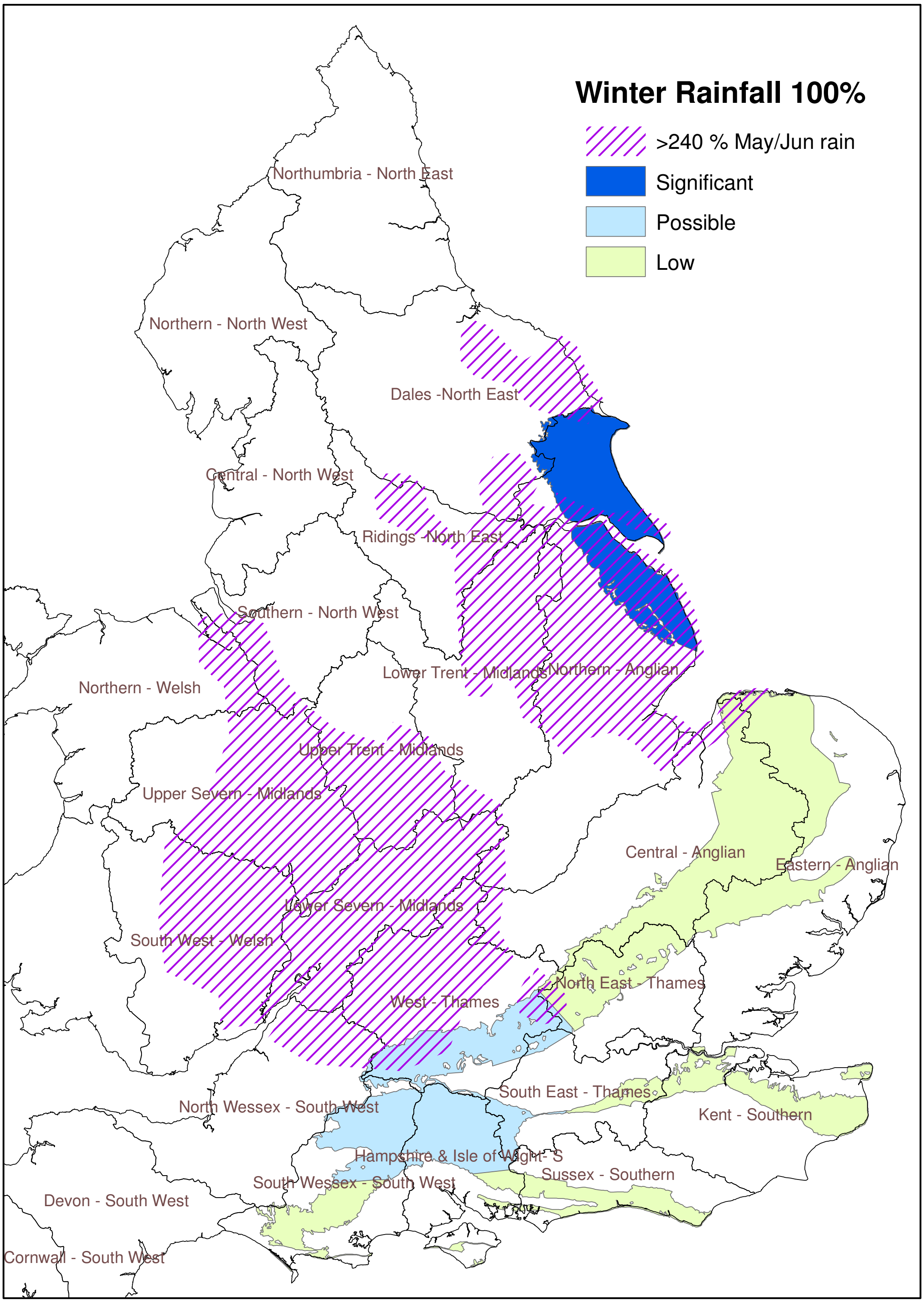

Figure 8 Areas of the Chalk outcrop at risk from groundwater flooding assuming 100% average winter rainfall

Autumn 2006 was the warmest on record for the UK and was also wetter than the 1971-2000 average. This year we move towards autumn from a summer that is already the wettest for England and Wales since 1912 and, up to 21 August, the coolest for the UK since 1998.

Our forecasting methods indicate that high pressure systems to the west of the British Isles may be more frequent than is usually the case in autumn. This suggests the following outlook for the UK for Autumn 2007.

- Most likely to be warmer than the 1971-2000 average, though cooler than last autumn;
- Average or below-average rainfall is more likely rather than above-average rainfall;
- Less frequent periods of very windy weather for autumn as a whole;
- Greater risk of fog, compared to normal, during the latter part of autumn.

Box 1 Met Office forecast for the autumn (Sept Oct) 2007