UK Hydrological Review 2000

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Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

2000

UK HYDROLOGICAL REVIEW

This Hydrological Review, which also provides an overview of water resources status throughout 2000, is a reformatted version of the original commentary released as a web report in 2001. Some of the data featured in this report, particularly the more extreme flows, may have been subsequently revised.

The annual Hydrological Reviews are components in the National Hydrological Monitoring Programme (NHMP) which was instigated in 1988 and is undertaken jointly by the Centre for Ecology & Hydrology (CEH) and the British Geological Survey (BGS) – both are component bodies of the Natural Environment Research Council (NERC). The National River Flow Archive (maintained by CEH) and the National Groundwater Level Archive (maintained by BGS) provide the historical perspective within which to examine contemporary hydrological conditions.

A primary source of information for this review is the series of monthly UK Hydrological Summaries (for further details please visit: http://www.ceh.ac.uk/data/nrfa/nhmp/nhmp.html). The river flow and groundwater level data featured in the Hydrological Summaries – and utilised by many NHMP activities – have been provided by the Environment Agency (EA), Natural Resources Wales - Cyfoeth Naturiol Cymru, the Scottish Environment Protection Agency (SEPA) and their precursor organisations. For Northern Ireland, the hydrological data were sourced from the Rivers Agency and the Northern Ireland Environment Agency. The great majority of the reservoir level information has been provided by the Water Service Companies, the EA, Scottish Water and Northern Ireland Water (formerly Water Service). The generality of meteorological data, including the modelled assessments of evaporation and soil moisture deficits featured in the report, has been provided by the Met Office. To allow better spatial differentiation the monthly rainfall data for Britain are presented for the regional divisions of the precursor organisations of the EA and SEPA. The Met Office monthly rainfall series are Crown Copyright and may not be passed on to, or published by, any unauthorised person or organisation. The provision of the basic data, which provides the foundation both of this report and the wider activities of the NHMP, is gratefully acknowledged.

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For further information about the National Hydrological Monitoring Programme please visit: http://www.ceh.ac.uk/data/nrfa/nhmp/nhmp.html

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Hydrological Review of 2000

2000 Summary

2000 was another relatively warm year and - with moist westerly airflows predominating - a remarkably wet one. England and Wales recorded its highest annual rainfall total since 1872 and the UK total ranks as the second highest since 1903. Despite near-record actual evaporation losses, water resources remained healthy throughout the year in almost all regions. A notable drought affected western Scotland (and parts of Northern Ireland) during the summer, but the most significant hydrological episode during 2000 was the exceptionally sustained rainfall over the September-December period - the wettest four-month sequence across England and Wales (for any start month) in a series from 1766. Over this timespan some areas in the South-East exceeded their annual average rainfall - a remarkable occurrence in the UK context. The resulting river flows were similarly extraordinary. Like the snowmelt-generated flooding of March 1947, the winter of 1962/63 and the summer of 1976, the impact of the protracted flooding over the last three months of 2000 (and, in some areas, extending well into 2001) has imprinted itself on a generation. In terms of the geographical spread and duration of inundation (or, in smaller responsive catchments, its frequency), the flooding has very few modern parallels. The events served to underline the importance of floodplain development, catchment management and agricultural practices in contributing to, or moderating, flood risk. Coming at a time of substantial interest in climate change, hydrological conditions during 2000 have focussed attention on the need to identify and quantify any emerging trends in extreme rainfall, river flow and groundwater recharge patterns.

Though less warm than most years over the preceding decade, mean temperature in 2000 again exceeded the average - in the last 13 years only 1996 has fallen below the 1961-90 mean. Correspondingly, potential evaporation (PE) totals for Great Britain were around 10% above average (based on MORECS estimates) - but still the lowest since 1993. By contrast, actual evaporation losses (AE) were the third highest on record, exceeded only by 1998 and 1999. The outstanding AE losses over the last three years reflect the relatively modest periods during the summer when AE losses have been constrained by high soil moisture deficits. In 2000, even lowland soils remained moist well into the early summer and, following a brief period with relatively high soil moisture deficits, soils wetted up very rapidly in September and October. Saturated soils - at a time when, in the eastern lowlands, soils are normally capable of absorbing significant further rainfall - were an important contributory factor to the exceptional autumn flooding. Whilst high evaporation losses were of agricultural importance (e.g. in July), their overall impact on water resources was modest. Reservoir contents for England and Wales as a whole remained above 80% of capacity - and well above the seasonal average - throughout the year. The seasonal recovery of stocks through the autumn was especially dramatic and, despite drawdown in some major reservoirs to increase flood storage capability in the late autumn and early winter, overall stocks exceeded 96% of capacity by early December (Figure 1). Overall stocks have remained well above the monthly average since early 1998 - a notable contrast to the relatively depressed stocks which characterised much of the early- and mid-1990s (see Figure 2).

2000 was a remarkable year for river flows. Flooding was common in January and April/May as well as during the major and protracted flood episode which began in early October. Unsurprisingly therefore, annual runoff totals were the highest on record in many catchments - particularly in southern Britain. More than 60% of catchments in England and Wales registered new maximum annual runoff totals, and

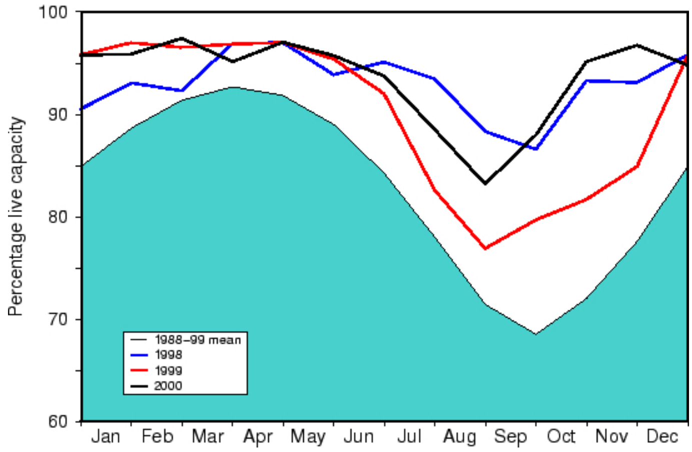


Figure 1 *Comparison between the within-year variation in overall reservoir stocks for England and Wales in recent years.*

Data sources: Water Services Companies and the Environment Agency.

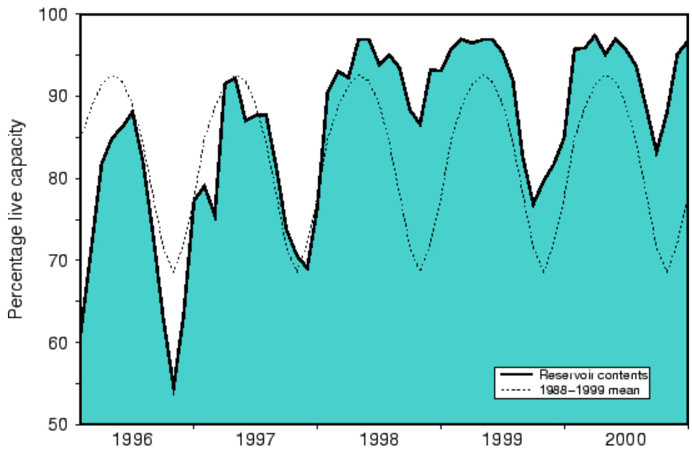


Figure 2 *A guide to the variation in overall reservoir stocks in England and Wales 1996-2000.*

Data sources: Water Services Companies and the Environment Agency.

existing peak recorded flows were superseded in many rivers where flow measurement has been undertaken for less than 30 years. Significant periods of low flow during 2000 were largely confined to north-western Scotland and the Western Isles, during late May and August especially. Elsewhere, flows generally remained well above the seasonal average (except during the late summer). Annual runoff variations for England and Wales - expressed as percentage departures from the long term average - are shown on Figure 3; the figures are based on outflows from a network of major river basins. Runoff for 2000 was more than 50% greater than average and the highest in a 40-year series by a wide margin. Notably high runoff has been registered for each of the last three years but there is little evidence of any long term trend (Figure 3). Scotland also recorded its highest annual runoff, marginally eclipsing the 1990 total (Figure 4). Runoff for Scotland shows a significant increase over the last 30 years, but an important contributory factor to this tendency is the unusual dryness of the early 1970s which serve to exaggerate the apparent steepness of the trend.

Most major aquifers are located in the normally drier southern and eastern regions of the country. One consequence is that groundwater recharge is normally only a modest proportion of annual rainfall - less than 20% in many eastern outcrops where much the greater part of the rainfall is accounted for by evaporative losses. In 2000 however, the normal north-west/south-east rainfall gradient across the UK was greatly moderated as synoptic patterns favoured rainfall over the English Lowlands. Rainfall over most of the more important aquifer outcrop was more than 50% above average. Due to evaporation losses, the relationship between rainfall and recharge is a non-linear one, and in 2000, the additional 30-40% of rainfall translated into recharge totals three or four times the average in parts of the eastern Chalk; recharge was remarkably abundant over the last three months of the year. Generally, groundwater levels remained above average in index wells and boreholes throughout the spring and early summer, and record levels followed an unprecedented seasonal recovery through the autumn. Over the last six weeks of 2000 recharge exceeded the annual average in parts of the South-East and many boreholes and wells overflowed. As rapidly rising water-tables reached the surface protracted 'clear-water' flooding was experienced on an unprecedented scale, being especially widespread in the chalk downlands of southern England.

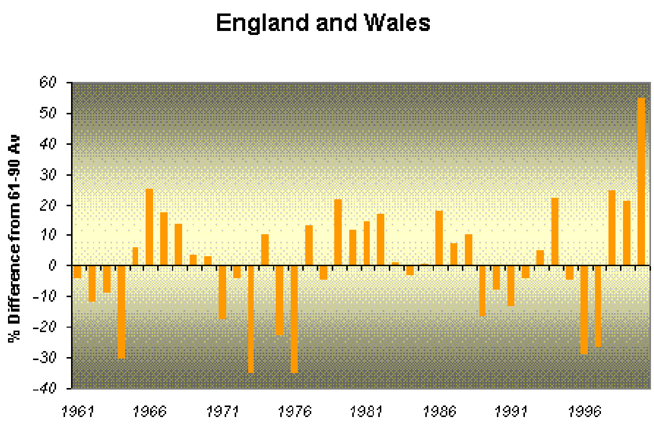


Figure 3 *Index of total runoff for England and Wales 1961-2000.*

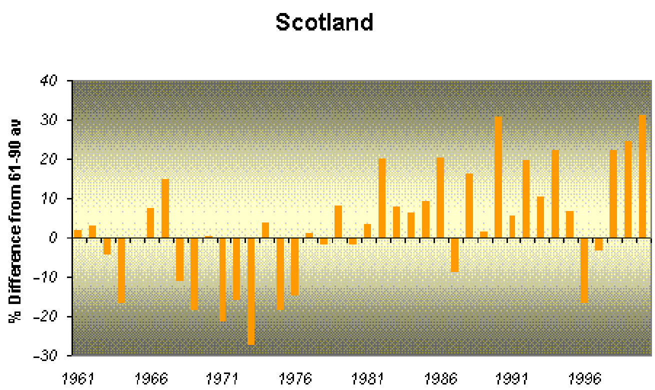


Figure 4 *Index of total runoff for Scotland1961-2000.*

Hydrological conditions throughout most of the UK during 2000 were very unusual. Some consistency with climate change scenarios could be recognised (e.g. above average temperatures and enhanced rainfall seasonality) but the year was distinct more for its singular nature than a reinforcement of any compelling hydrological trends. The variability in runoff and recharge rates over the last decade has extended the recorded range at many hydrometric monitoring stations. But the shortness of most records, the large range of natural variability, and the increasingly pervasive impact of man on runoff and recharge patterns dictate caution in extrapolating from recent tendencies to any long term trends. In a water resources context, it is essential to recognise that river flows, reservoir replenishment and aquifer recharge rates reflect a complex interaction between precipitation (its type, intensity, and distribution in time and space), evaporative demands, soil moisture conditions, land use and, in many areas, water abstractions patterns. Through time, some of these factors may have a reinforcing effect; others may be expected to counterbalance one another. Increased winter rainfall may, for example, counterbalance increased annual evaporative demands. It is important therefore that the UK maximises it capability to both recognise hydrological trends and assess the relative contributions of climate-driven influences and those more directly attributable to man.

Rainfall

The relentless passage of active frontal systems throughout much of 2000 resulted in exceptionally high annual rainfall totals across large parts of the UK. Figure 5 shows provisional regional annual rainfall totals for 2000 together with the corresponding percentages of the 1961-90 average. All regions reported above average rainfall but the greatest positive anomalies were in the South-East. Scotland and Northern Ireland both registered well above average annual rainfall totals - albeit significantly lower than those of 1998 and 1999. Correspondingly, 2000 was the third notable wet year in succession across the UK; provisionally the January 1998-December 2000 rainfall total is the highest 36-month accumulation on record for the UK, in a series from 1900. Rainfall in Northern Ireland over the last 15 years has been around 6% greater than the preceding average whilst in Scotland recent rainfall totals have been even more outstanding, contributing to a post-1985 average around 15% higher than the preceding mean. In 2000 however, the most exceptional rainfall was experienced across England. Most regions registered 25% or more above the 1961-90 annual average and some parts of the South-East received more than twice the monthly average rainfall in April, May, October and November. For the Thames Valley, 2000 was the second wettest year (after 1903) in a series from 1883. Sustained periods of below average rainfall were largely confined to north-western Britain (and parts of Northern Ireland). Many catchments in western Scotland registered significantly below average rainfall for five successive months beginning with May (see Figure 6) - producing very large rainfall deficiencies by the early autumn; very unusually, rainfall over this period for the South-East approached that for parts of north-western Britain.

January was relatively dry in many areas - the English Lowlands especially - but February was the seventh wettest (for the UK) in the last 50 years, and winter (December-February) rainfall totals exceeded the average by a wide margin in western and northern regions. For Scotland, the provisional winter total ranks second highest (after 1994/95) in a series from 1869;1997/98 and 1998/99 were also very wet. Northern Ireland also registered a wet winter, and in England and Wales only some lowland - mostly eastern

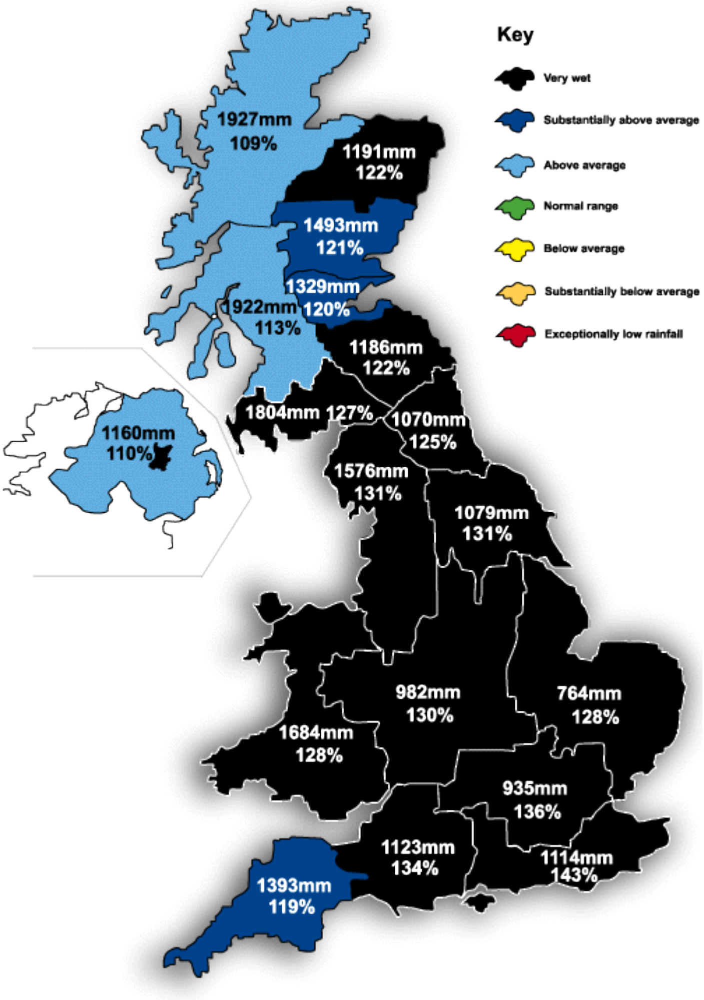


Figure 5 *Annual rainfall (provisional) for 2000 in mm and as a percentage of the 1961-90 average.*

Data source: UK Met Office.

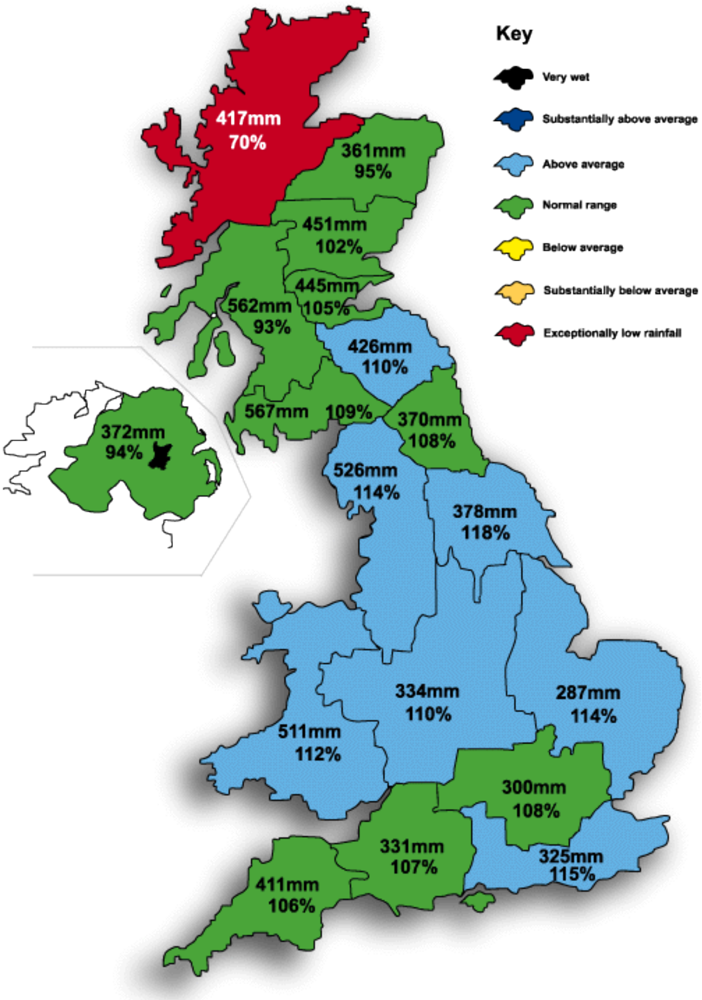


Figure 6 *May - September 2000 rainfall (provisional) for 2000 in mm and as a percentage of the 1961-90 average.*

Data source: UK Met Office.

- districts fell below the 1961-90 mean. Except in western Scotland (including the Western Isles), March was dry - notably so in the east. Synoptic conditions were much more variable in April but, nationally, it was an extremely wet month - closely matching 1998 as the wettest April on record for the UK, and the wettest in a series from 1766 for England and Wales.

Rainfall is most hydrologically effective over the November-April period when evaporation losses are very modest and soils generally moist. In this timeframe, the 1999/2000 rainfall was above average in all regions, and exceptionally high in western and northern Scotland. The corresponding periods in 1997/98 and 1998/99 were also notably wet across the UK - this sequence of wet winter and early spring periods largely explains the transformation in water resources since the drought conditions in the mid-1990s. May rainfall totals in 2000 were modest in Scotland but, after a dry start to the month, very high throughout southern Britain - around twice the long term average in many catchments in the English Lowlands. Locally, thunderstorms produced some very high intensity rainfall - on the 7th, 65mm fell in two hours at Bracknell (Berkshire) - with hailstones up to 15mm in diameter. For England and Wales, the combined April/May rainfall total was the highest since 1782. Accordingly, spring (March-May) rainfall totals were substantially above average in much of England, but modestly below in Northern Ireland and parts of Scotland.

The summer began with a notable dry spell - some localities (e.g. in central southern England) reporting <2mm of rainfall over the first 18 days of June. This proved an atypical interlude; weather patterns were substantially more unsettled thereafter. Nonetheless, June rainfall totals were mostly well below average - parts of eastern England reported their third driest June since 1976. In western Scotland rainfall deficiencies were becoming significant after four successive months with below average rainfall. July was dull and relatively cool in southern Britain but the limited rainfall added to a cluster of dry Julys - six of the last eight have produced below average rainfall for the UK as a whole. Much of northern and western Scotland was particularly dry and some local water supply difficulties were encountered; late in the month ferries were used to augment supplies in Tiree in the Western Isles. In August thunderstorms produced locally severe flooding in the South particularly (e.g. Knaphill in Surrey reported 45mm in around an hour on the 21st). Those localities which bore the brunt of the storms registered notably high monthly rainfalls (e.g. Aldegrove in Northern Ireland) but, generally, August rainfall totals were appreciably below average. Notwithstanding an unsettled complexion to the weather through the summer, the June-August rainfall totals were significantly below average in almost all regions, adding to a recent tendency for below average summer rainfall - the mean over the last 25 years for England and Wales is around 15% below the preceding average.

'Indian Summer' conditions in early September rapidly gave way to more autumnal weather patterns as a vigorous westerly airflow became established in mid-month - heralding a remarkably wet episode which extended through the autumn and well into the spring of 2001. Many rainfall records were eclipsed over this period. September rainfall was the highest since 1981 for England Wales but drought conditions persisted in parts of the Western Isles. October was considerably wetter - the equal second wettest on record for the UK and flooding was very severe in the South East especially. An outstandingly wet day - the 29th, when around 30mm fell across England and Wales - triggered the extension of flood conditions to much of the country. As a consequence of the very wet early autumn, rainfall over the May-October period exceeded that for the preceding six months - a common occurrence prior to 1900 but only the 10th time in the last 30 years. Vigorous frontal systems continued to cross the UK in November - and again regional rainfall totals exceeded the average, by wide margins in most regions. For England and Wales it was the second wettest November in the last 50 years. Mild and very wet conditions continued into December with abundant rainfall until Christmas. By the end of the year rainfall accumulations were extraordinary. The September-December period was, the wettest four-month sequence in the 335-year England and Wales rainfall series, and unprecedented n-month rainfall totals continued to be established well into 2001.

Evaporation and Soil Moisture Deficits

Evaporation is perhaps the least tangible of the processes in the water-cycle but evaporation losses account for around 40% of the annual rainfall on a UK-wide basis. Evaporation may occur directly from the soil, from open water surfaces, or as transpiration from plants. Knowledge of evaporation rates - and soil moisture status - is essential to any evaluation of water resources. Potential evaporation (PE) is the evapotranspiration loss which would occur from a continuous vegetative cover amply supplied with moisture. PE losses are highly seasonal and primarily a function of solar radiation, temperature, windspeed and humidity. From the spring (in most years), drying soil conditions and the response of plants to the more limited water availability restricts the ability of transpiration to proceed at its potential rate. Thus, in the absence of favourable soil moisture conditions, actual evaporation (AE) rates fall below PE rates - appreciably so in dry summers. Given normal rainfall, the accelerating evaporation demand through the spring leads to a progressive drying of the soil profile and the creation of a soil moisture deficit (smd); in the summer smds are normally high enough to greatly reduce river flows and replenishment of aquifers. When plant activity and evaporation rates slacken in the autumn, rainfall wets-up the soil profile heralding the seasonal recovery in runoff and aquifer recharge rates.

Although average temperatures were appreciably below the mean for the preceding two years, 2000 still ranks in the warmest 20 years in the Central England Temperature (CET) series which extends back to 1659. Eight of the last 12 years feature in this warm group, and average temperatures since 1988 has been about 1° centigrade above the preceding average. In 2000, only October registered a mean temperature below the 1961-90 average; February, March, August and December were notably warm relative to the monthly average.

Provisional potential evaporation totals for 2000 - calculated for 40km squares across Great Britain - are shown in Figure 7; they were derived using the MORECS procedure, and assume a grass cover. Annual totals range from less than 450mm in the Scottish Highlands to greater than 650mm in parts of southern Britain. As usual coastal locations, where wind is a significant factor, tended to have the highest totals. In percentage terms PE totals for 2000 were close to the 1961-90 average in all regions. Nonetheless, for England and Wales as a whole PE losses were the lowest since 1993 and substantially less than those registered for each year in the 1995-1999 period. By contrast, annual actual evaporation (AE) losses were, nationally, the third highest in a series from 1961; the 1998 and 1999 totals were marginally higher. AE totals for 2000 were within the 460-650mm range across the great majority of Great Britain (see Figure 8) and generally fell only modestly short of the corresponding PE totals (see below). Across most of western and northern Britain AE losses were within 10% of the long term average (see Figure 8), but in the English Lowlands totals 10-15% above average were typical; record annual losses characterised much of East Anglia (parts of Wales and the Midlands also).

In most years, AE losses fall only a little short of the corresponding PE totals throughout the wetter northern and western regions of the country. This was true of 2000 also but, importantly, annual AE totals also approached PE totals across much of the English Lowlands. This confirms that evaporation losses were constrained for only a limited period by very dry soil conditions (which reduce transpiration rates). Figure 9 illustrates the development and decay of soil moisture deficits (indicated by the brown shading), together with monthly PE and AE totals for 2000 for six representative MORECS squares - note that the PE and AE traces are often co-incident. As usual, PE losses peaked over the May-August period but, for the summer half-year, totals were substantially lower than in a number of recent years (1990 and 1995 especially). More notable is the comparison between AE losses in lowland catchments - as represented by squares 151 and 108 - during the summers of 1996 and 1997, and those of 2000; the latter being around three times those for the exceptionally dry and hot summer of 1995.

Soil moisture deficits began to develop early in the year (typically during February) but were largely eliminated during the wet spring. Soils began to dry-out briskly in late May but, with only a limited period over which to develop, approached the seasonal average only in late July and August (see Figure 9); north-western Scotland was an exception to this pattern; soils remained unusually dry through much of the summer. Despite the late onset of the drying phase, smds in parts of eastern England were - by early September - sufficiently high to require average rainfall through the autumn to initiate groundwater recharge by the early winter. Such a lag in the seasonal recovery of runoff and recharge rates is a normal occurrence. In the event, however, recoveries in 2000 were very dramatic. By mid-October smds had been largely eliminated and by month-end most catchments were saturated. In many recent years, dry spells in the autumn have re-established modest deficits in the eastern lowlands but in 2000 soils, once saturated, remained so (until well into 2001). This ensured a very lengthy recharge season, and a continuing flood risk across much of the country.

Although overall PE losses in 2000 failed to match those of the warmest years in the preceding decade, the tendency for PE totals to exceed the long term average continued. Since 1989, PE losses have averaged around 7% greater than the 1961-90 mean. AE losses for the country as a whole have also been appreciably higher than average - but regional, and year-on-year variations have been substantial, especially in the driest eastern catchments where maximum smds have also exhibited a wide range over the last decade.

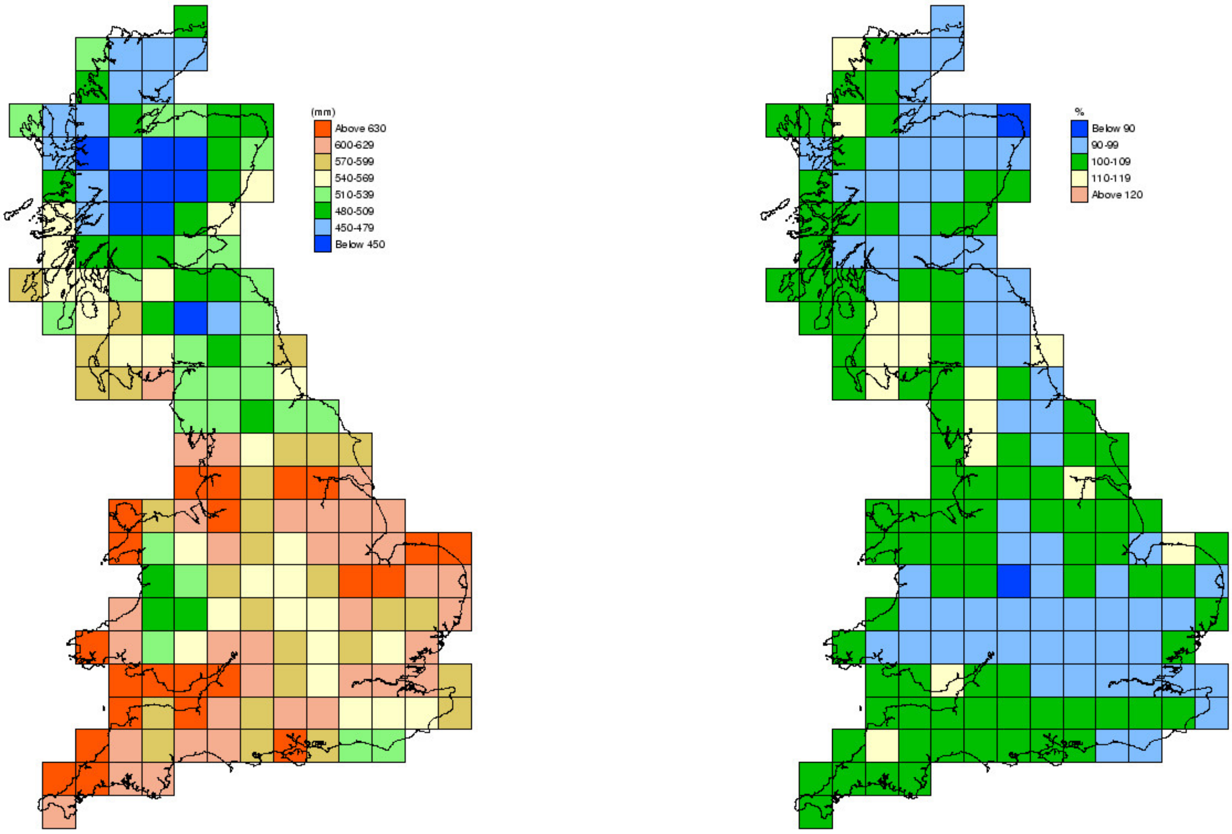


Figure 7 *Potential evaporation totals for 2000 in mm and as a percentage of the 1961-90 average.*

Data source: MORECS.

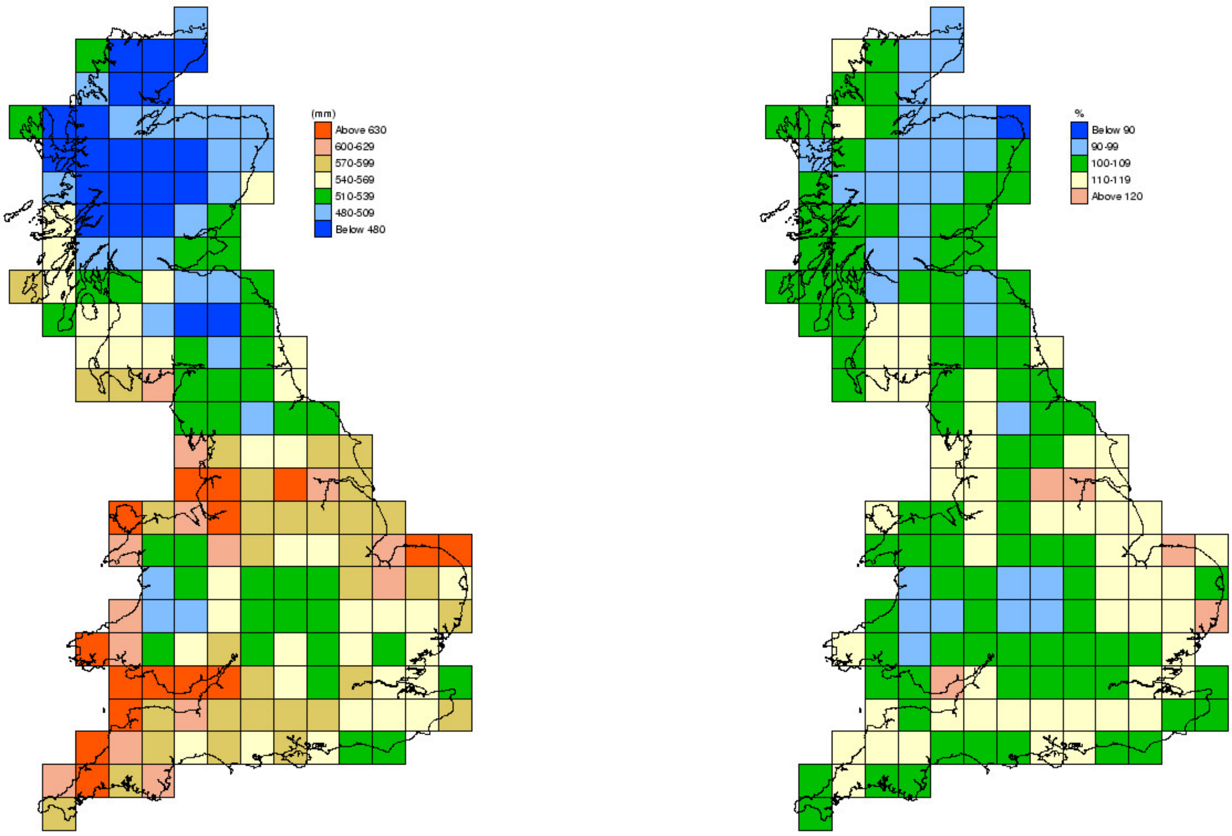


Figure 8 *Actual evaporation totals for 2000 in mm and as a percentage of the 1961-90 average.*

Data source: MORECS.

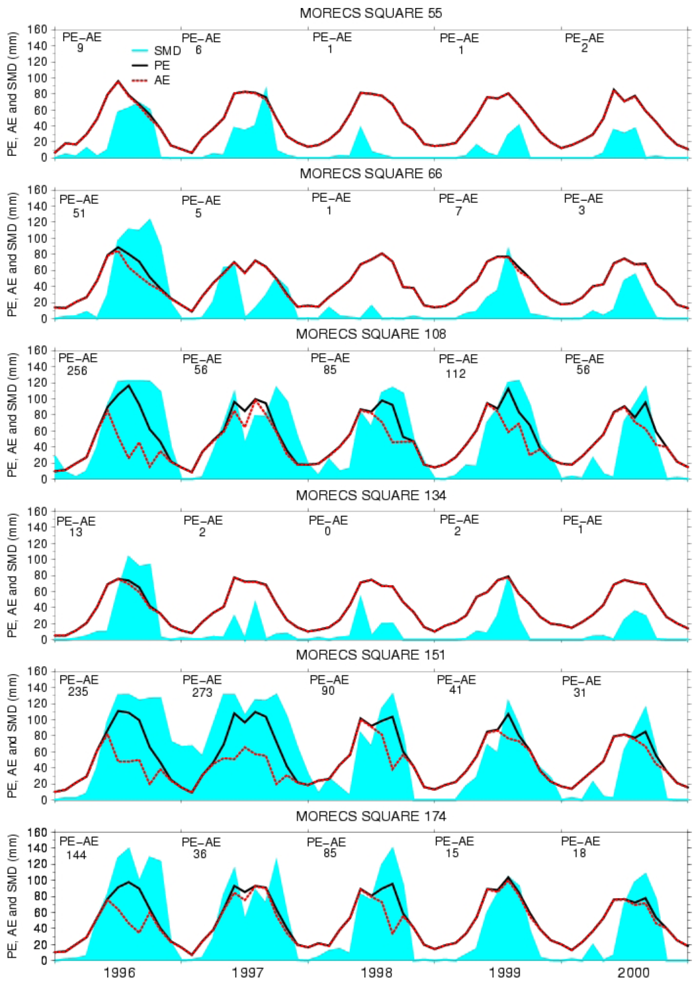


Figure 9a *The variation in potential evaporation, actual evaporation and soil moisture deficits for six MORECS squares 1996-2000.*

Data source: MORECS.

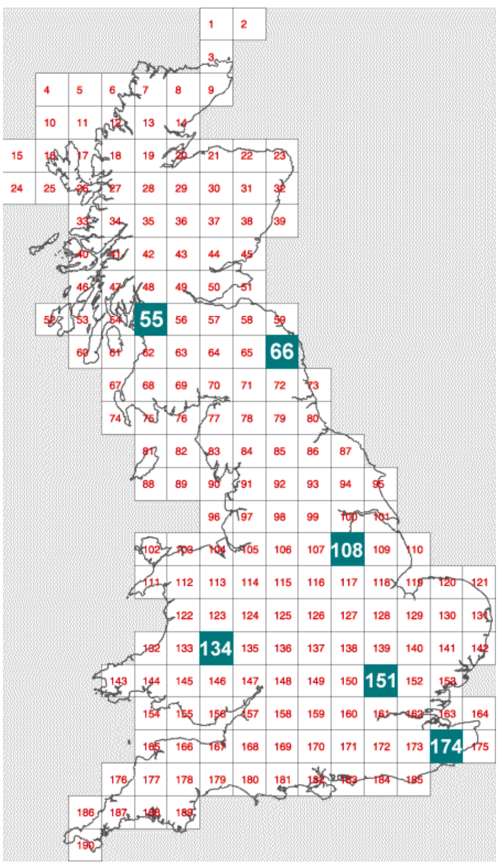


Figure 9b *MORECS Location Map: the location of the 40km squares and their associated reference numbers.*

River Flows

2000 has established a major new hydrological benchmark in relation to high river flows and the frequency/extent of flood events across large parts of the UK. An outstanding number of new river flow records (n-day accumulations in particular) were established during the 2000/2001 winter half-year. Many of the 2000 peak flows - the great majority of which occurred during the final three months - are subject to future review, but estimated return periods are in the 10-40 year range across much of England and Wales. Some peak flows were substantially more extreme; this was particulerly true of the English Lowlands but exceptional discharge rates were also recorded in southern Scotland, and in Northern Ireland where high spate conditions had also characterised the autumn and early winter of 1999. Many notable high flow gaugings were completed during late-2000 by the measuring authorities throughout the UK - often under very difficult field conditions - to help determine the magnitude of the peak flows but, in some areas, the extreme flood peaks served to emphasise limitations in the high flow performance of a number of network gauging stations.

Annual runoff for England and Wales for 2000 substantially exceeds that for any year in the 1961-2000 series. In large part, this reflects the very abundant runoff over the last three months of the year, but outflows were seasonally very high in the spring also. The annual outflow from Scotland was exceptional also. The Spey, Tweed, Cree and Clyde (each with records of 35 years or more) are amongst many major Scottish rivers which recorded new maximumun annual runoff totals. In Northern Ireland most catchments registered appreciably above average runoff, including the Annacloy which exceeded its previous annual maximum despite below average flows over the first five months of the year. Runoff across England and Wales was even more remarkable. In over 65% of gauged catchments the runoff total for 2000 was unprecedented. For the Severn (at Bewdley) the runoff total was the second highest in 80 years, and that for the Thames (at Kingston) is exceeded only by 1951 in a record from 1883. Many rivers in southern England exceeded previous maxima by very wide margins (e.g. the Mole and Itchen).

Daily mean flow patterns for 20 index gauging stations throughout the UK are shown in Figure 10; the 2000 hydrographs are illustrated by the solid trace and the shaded envelopes illustrate the maximum and minimum daily flows over the preceding record. An extension of the range of recorded variability in the September-December period is evident. In Scotland, river flows generally followed the normal pattern but with enhanced seasonal contrasts, particularly in the west where depressed river flows typified the

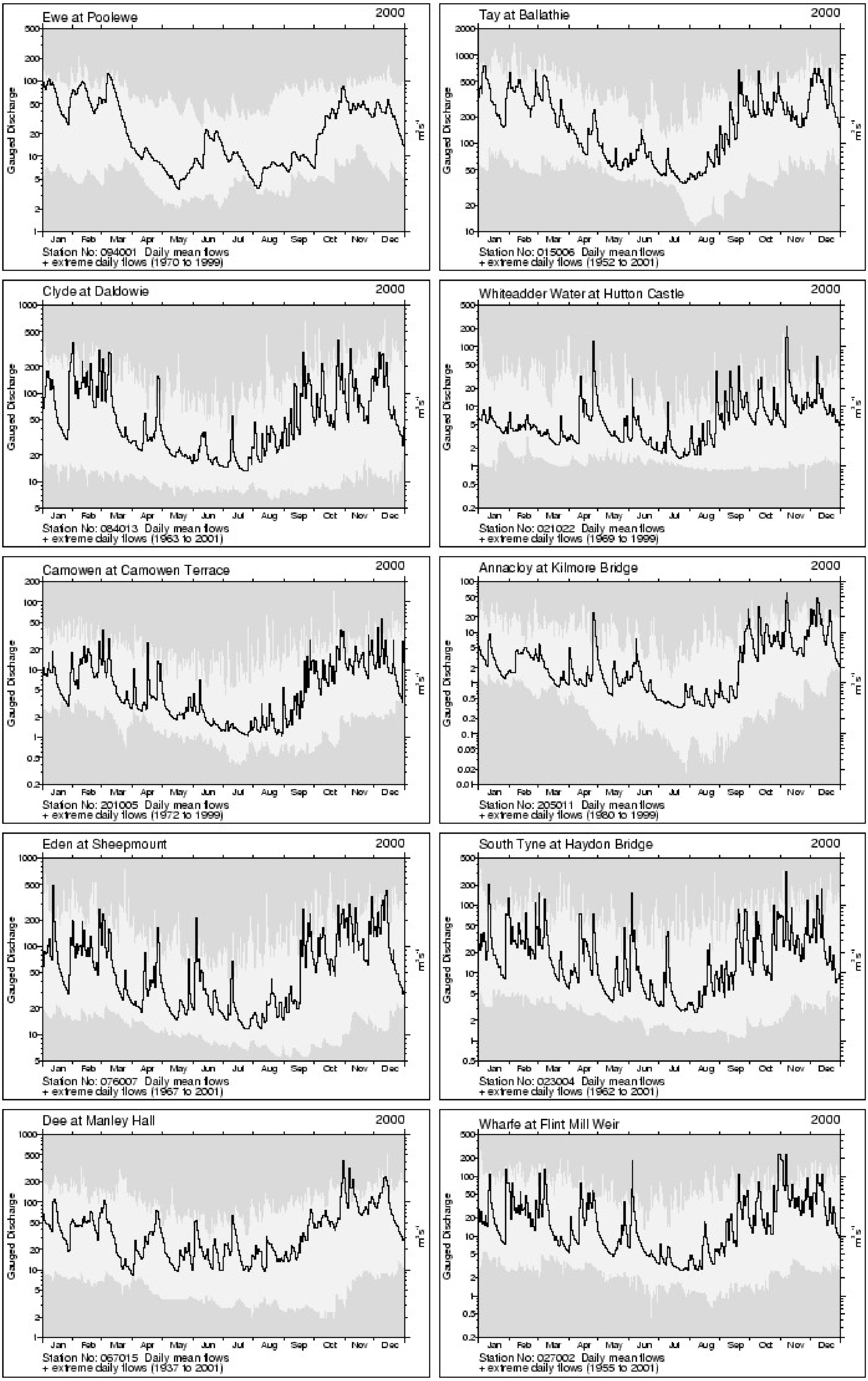


Figure 10 *Daily river flow hydrographs for 2000.*

Data sources: Environment Agency/Scottish Environment Protection Agency/Rivers Agency.

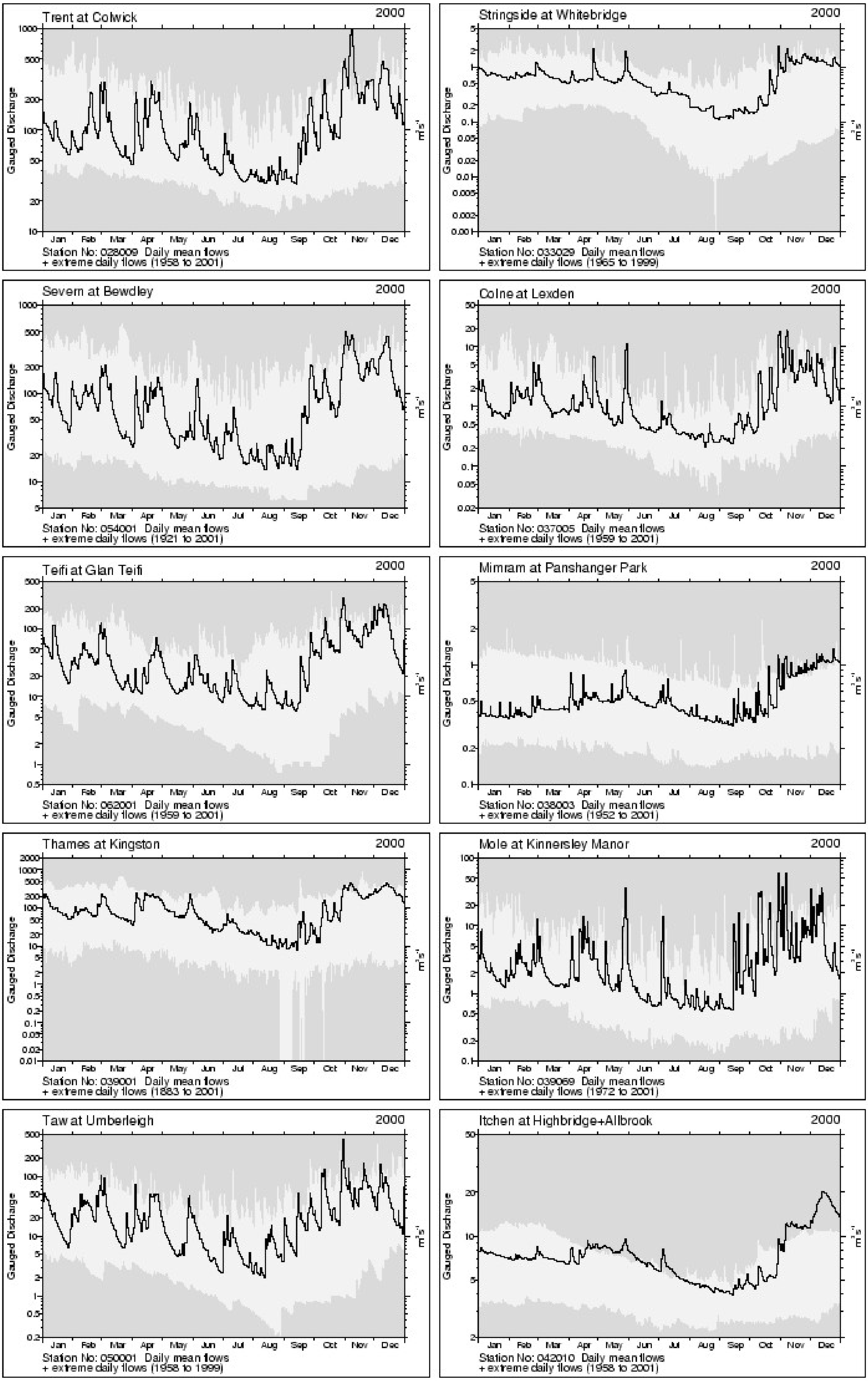


Figure 10 *(Contd.)*

late spring and late summer. Flows in England and Wales followed a less familiar pattern, in southern rivers especially. The influence of catchment geology was very evident with high baseflow contributions to summer flows and remarkably abundant groundwater outflows from the late autumn onwards.

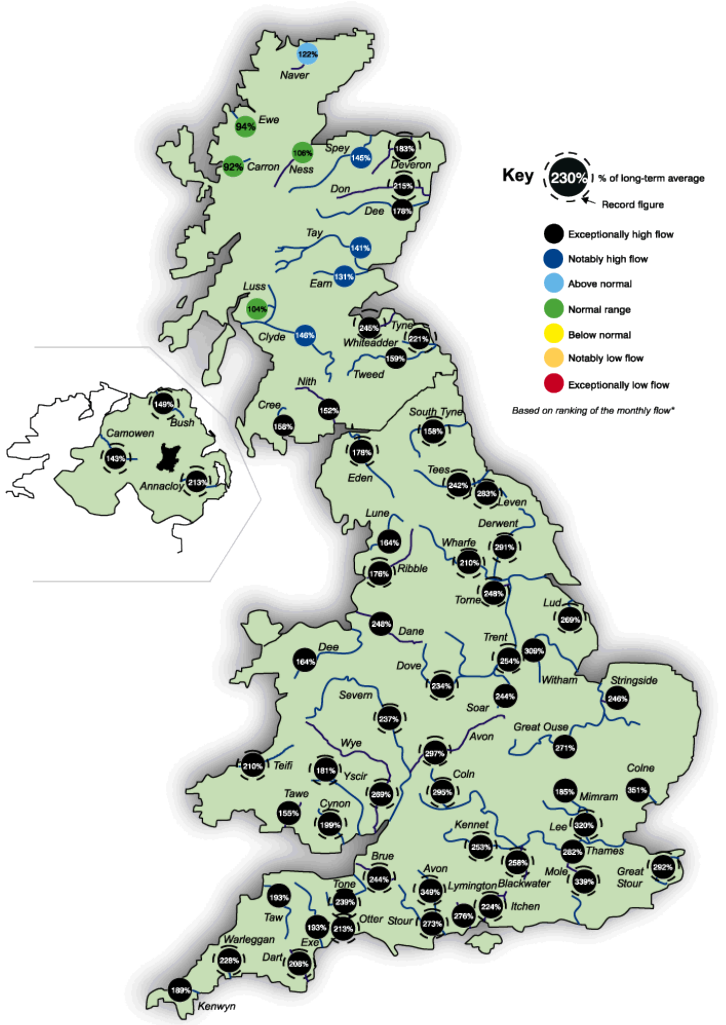
Significant flooding occurred in January (e.g. in Scotland around the 6-7th) but steep recessions in rivers draining impermeable catchments resulted in notably low flows around month-end (e.g. on the Medway and Wallington in southern England). February was characterised by repeated spates in western and northern catchments particularly, but the threat of flooding was moderated by the rapid passage of the rain-bearing low pressure systems - helpfully limiting storm rainfall totals. Some rivers, e.g. the Clyde, established new February runoff records, and winter (December-February) totals were among the highest on record for many rivers draining the Scottish Highlands. By contrast, winter runoff totals were generally a little below average in eastern Britain - particularly in responsive clay catchments. Spates continued in western Scotland through March and a number of record winter half-year runoff totals were established e.g. on the Spey and Ewe; abundant winter runoff has been a recurring feature of the recent past in rivers draining from the Highlands. March flows were below average throughout most of England and winter half-year runoff totals were depressed in some sheltered eastern catchments; this was also true of Northern Ireland where the Annacloy registered an October-March minimum in a series from 1978.

Contrary to the normal seasonal pattern, April saw a brisk recovery in flows with moderate flooding late in the month. Existing April runoff maxima were eclipsed in many catchments from the Leven (in the Tees catchment) to the Blackwater in Surrey. Recessions became established in May but were again reversed, albeit briefly, as storms late in the month triggered (mostly minor) flood alerts. Spate conditions were very infrequent in western Scotland and the continuing below average flow in rivers draining from the Mourne Mountains was reflected in seasonally low stocks in the Silent Valley reservoirs in Northern Ireland. Generally however, May runoff totals were amongst the highest on record, unprecedented in some permeable catchments in southern England (e.g. the Coln and Kennet). The seasonally late surge of recharge in southern Britain provided a boost to, already healthy, outflows from springs, but in impermeable catchments brisk recessions became re-established in June. They were however subject to further interruption by significant spates; on the 4th, the Wear, in north-eastern England, recorded its highest flow for over 20 years.

River flow recessions were steep during July but thunderstorms caused local interruptions, generating short-lived flood events; the impacts were especially severe in urban areas where the intensity of rainfall overwhelmed some local drainage systems (e.g. in Worthing and Belfast). Flows remained significantly below average in parts of northern Britain - the River Ness (at Ness-side) recorded its lowest July mean flow in a 27-year record. Thunderstorms were responsible for further flooding in August - on the 2nd, the rapid melting of hail drifts produced unusual but very localised flood events e.g. in Hull. Rather more widespread flooding occurred late in the month as flows increased briskly in many western and northern catchments. Nonetheless, summer (June- August) runoff totals were generally a little below average in Scotland, more so in the west. By contrast runoff in baseflow-supported rivers in southern England was amongst the highest on record, even in catchments with below average summer rainfall - e.g. in Hampshire and West Sussex.

The contrast between flows early and late in September was remarkable in many catchments as seasonal recoveries gathered momentum. In western Scotland spates in mid-month terminated a notable low flow phase - for some Highland rivers the April-September runoff was the lowest on record for any 6-month sequence (e.g. on the Ewe and Carron). With catchments saturated throughout most of the UK, the flood risk was high by early October. Bankfull, or higher, flows were remarkably persistent over the last three months of the year. Autumn (September-November) runoff totals were the highest on record over much of the country, and the October-December accumulations were outstanding over wide areas. The extreme runoff was associated with exceptionally widespread flooding, the extent and duration of which has few modern parallels. Several relatively distinct phases to the flooding could be recognised. Severe but mostly localised flooding, much of it in the South-East, during October was followed by exceptionally extensive floodplain inundations in early November and further widespread flooding in the second week of December. The frequency of flooding was a serious aggravating factor in many catchments across the English Lowlands, and elsewhere - in Northern Ireland three exceptional peak flows occurred in an eleven-week period. events Thereafter, steep recessions typified most western and northern rivers, but in impermeable catchments extremely high baseflows resulted in protracted spate conditions with many new December maximum flows established in the South.

For many gauging stations, especially those with flow records commencing in the last 30 years, 2000 saw a significant redefinition of the high flow regime - in England especially. A guide to runoff over the October-December period is shown on Figure 11; for most English catchments the runoff is unprecedented. Many rivers in southern Britain recorded well over twice



*Comparisons based on percentage flows alone can be misleading. A given percentage flow can represent extreme drought conditions i permeable catchments where flow patterns are relatively stable but be well within the normal range in impermeable catchments where th natural variation in flows is much greater.

Figure 11 *October-December 2000 river flows as a percentage of the long term average.*

Data sources: Environment Agency/Scottish Environment Protection Agency/ Rivers Agency.

the average river flow over this period - a particularly rare occurrence in groundwater-fed rivers (e.g. the Itchen) which have relatively stable flow regimes. Outstanding peak flows were reported for many southern, and some other, catchments but runoff accumulations in the 30-90 day timespan were remarkable across much of the country. The very unusual flow patterns experienced throughout much of 2000 are evident from the flow duration curves featured in Figure 12. These curves allow the proportion of time that river flows fall below any given threshold to be identified. Generally, flows during 2000 exceeded the long term average throughout the flow range. For the Thames, the 5% and 95% exceedance flows for 2000 were 157% and 175% respectively of the corresponding flows for the pre-2000 record. A few exceptions to the general pattern can be found: the flow duration curve for the Camowen in Northern Ireland differs only marginally from the 1972-1999 trace, and the Mimram is typical of the slower responding eastern Chalk rivers where flows remained mostly below average following the droughts of the mid-1990s until the remarkable late-2000 recovery gained momentum - heralding record flows in the late winter and early spring of 2001.

Groundwater

Most major aquifer outcrop areas are in the driest parts of the country - predominately the English Lowlands where groundwater is the principal contributor to water supply. In water supply terms the Chalk, which outcrops in eastern and southern England, is the major aquifer; the Permo-Triassic sandstones are regionally important - in the Midlands especially. Away from the more westerly aquifer outcrop areas groundwater replenishment (or recharge) in a typical year ranges from 500mm to less than 100mm in the most easterly outcrops. The non-linear relation between rainfall and recharge (see 'Summary') is associated with large year-on-year variations in recharge totals. This volatility has been well illustrated over the last decade, and culminated in a truly remarkable recharge episode over the final third of 2000 - which continued well into the spring of 2001.

Figure 13 shows 1996-2000 groundwater level hydrographs for a selection of index wells and boreholes throughout the UK. Five-year plots have been used to encompass the outstanding range in groundwater levels over the recent past, and also because the volume of groundwater storage in most aquifers reflects recharge over several winters. The groundwater level trace is shown together with the monthly maximum and minimum levels for the pre-1996 record. The normal seasonal variation in levels is clearly evident in the hydrographs for most sites; other common features include the erratic recharge pattern over the 1999/2000 winter half-year and, most notably, the extraordinary seasonal recovery late in the year. In overall resources terms, an important contrast can be drawn between the last three years - when groundwater levels have been mostly above average, and the depressed levels of the 1995-1997 period.

After substantial recharge late in 1999, infiltration during January 2000 was less than 40% of the monthly average over much of southern Britain. Although infiltration was much healthier in February, soil moisture deficits (smds) began to build around month-end and increased through March when rainfall across much of the Chalk outcrop was less than half the long term average. At the end of the winter half-year (October-March) groundwater levels had fallen considerably from their December 1999 peaks but were generally well within the normal range for the early spring. April is often a pivotal month in groundwater terms, accelerating evaporation rates commonly bring the winter recharge season to an end, in eastern outcrops especially. In 2000 however, the sustained rainfall generated a seasonally late surge of recharge which continued into May - infiltration over the two months was more than twice the long term average in most outcrop areas - generating a rise in

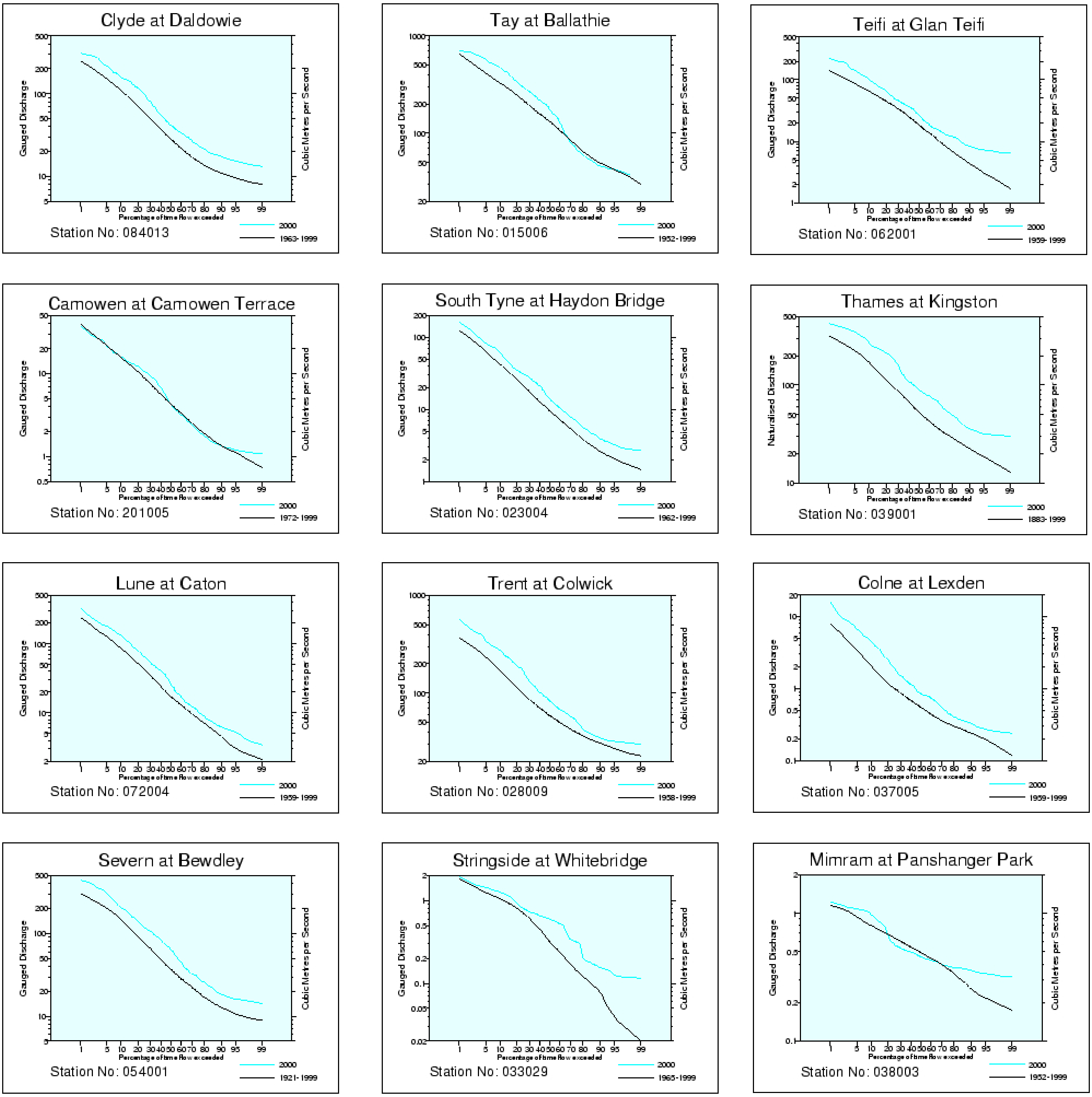


Figure 12 *Flow duration curves for 2000 (in blue) and the preceding record.*

Data sources: Environment Agency/Scottish Environment proection Agency/Rivers Agency.

water-tables at a time when recessions have normally become established.

The delay in the seasonal downturn meant that, entering the summer, groundwater levels were significantly above average in most regions. Although recessions were brisk in July, August and early September (see Figure 13), minimum levels recorded in 2000 were generally above the average (for the early autumn), and well above the minima which typified the early and mid-1990s. An exception was the slow-responding Morris Dancers borehole in the Permo-Triassic sandstones of the East Midlands; here sustained soil moisture deficits in the mid-1990s provided limited opportunities for aquifer recharge and levels, which are also influenced by groundwater abstraction, became very depressed. In 2000, groundwater levels at Morris Dancers remained below pre-1998 minima throughout most of the year.

The rapid elimination of smds in September and October initiated an early, and remarkably steep,

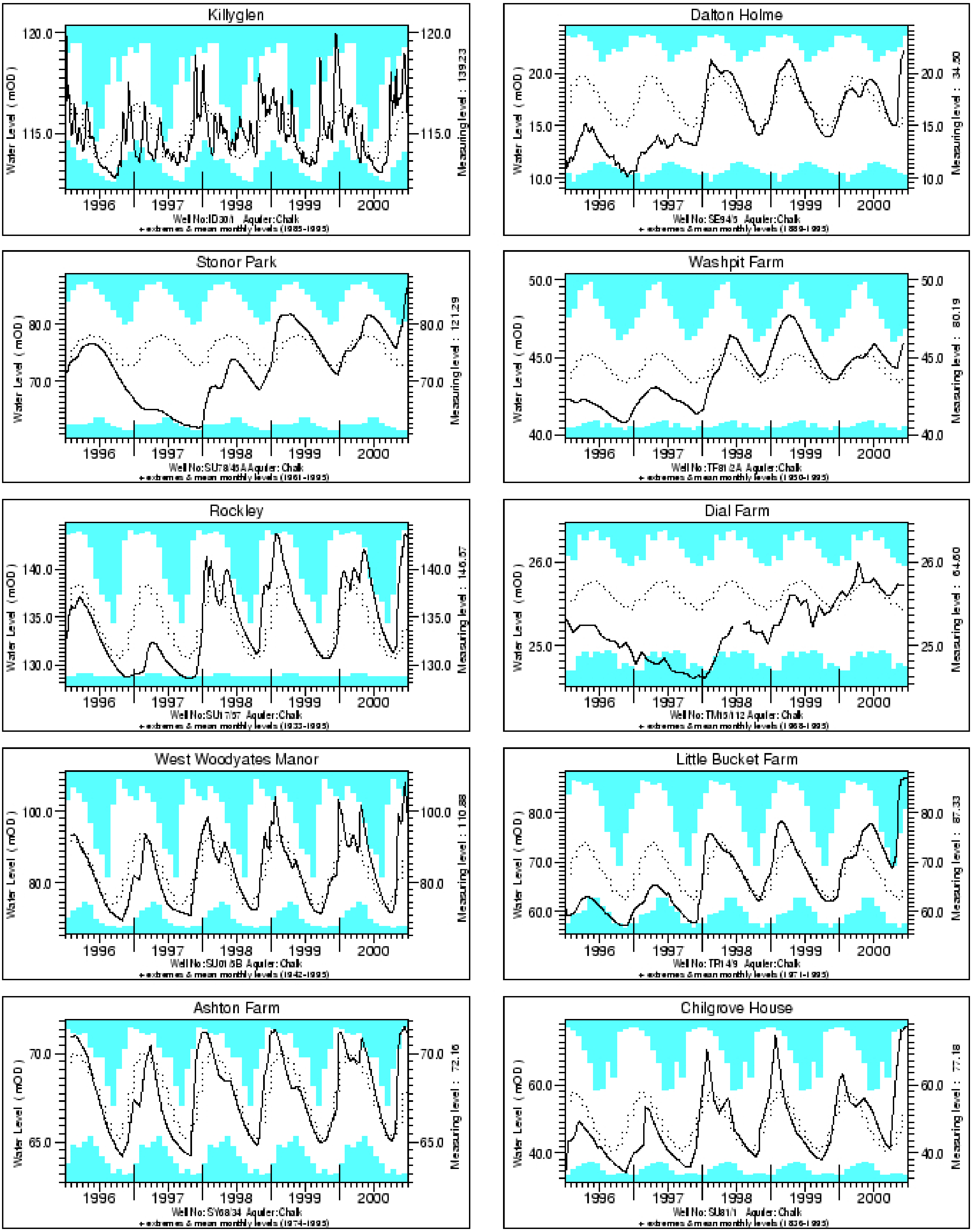


Figure 13 *Groundwater level hydrographs 1996-2000.*

Data sources: Environment Agency/Scottish Environment Protection Agency/Rivers Agency.

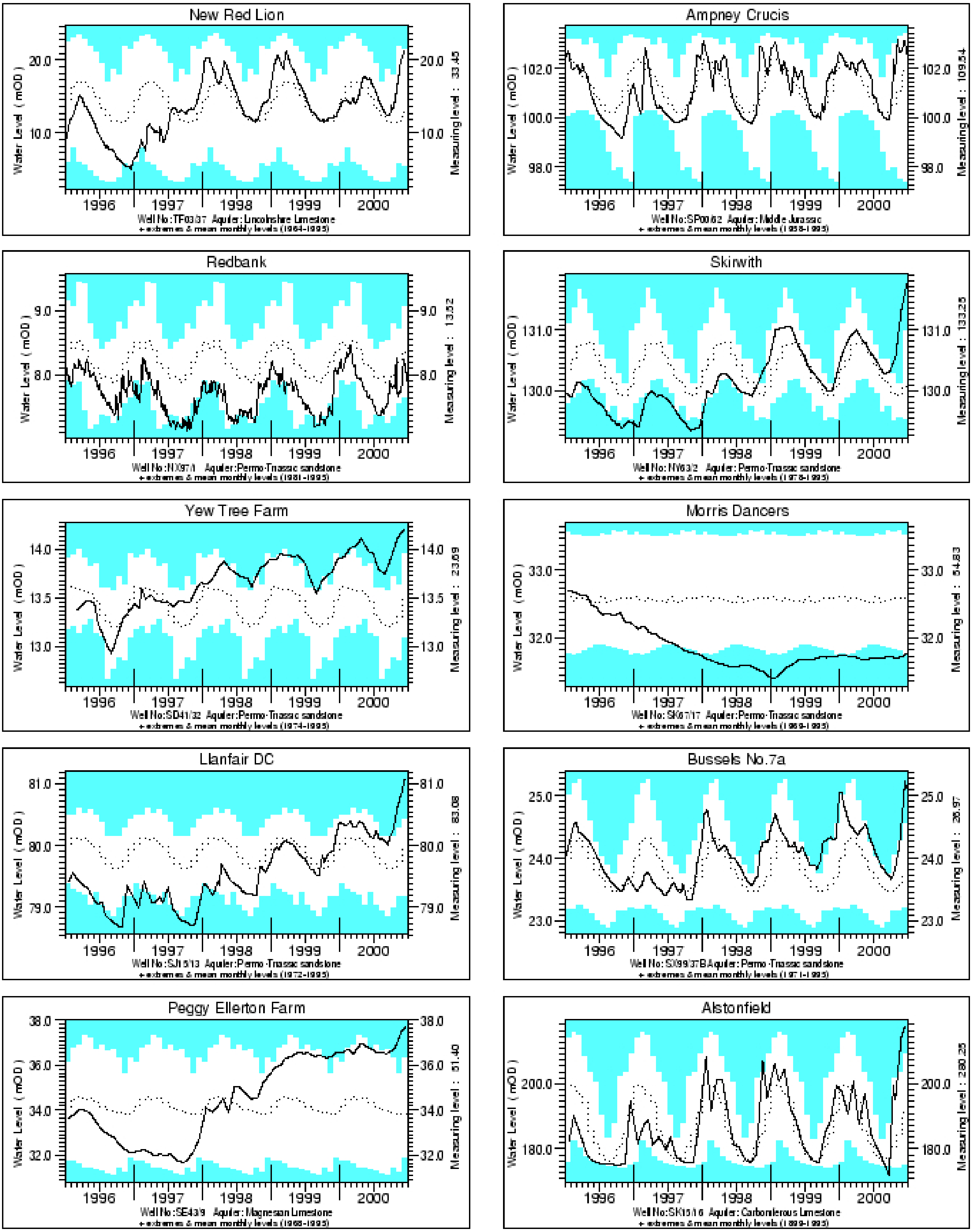
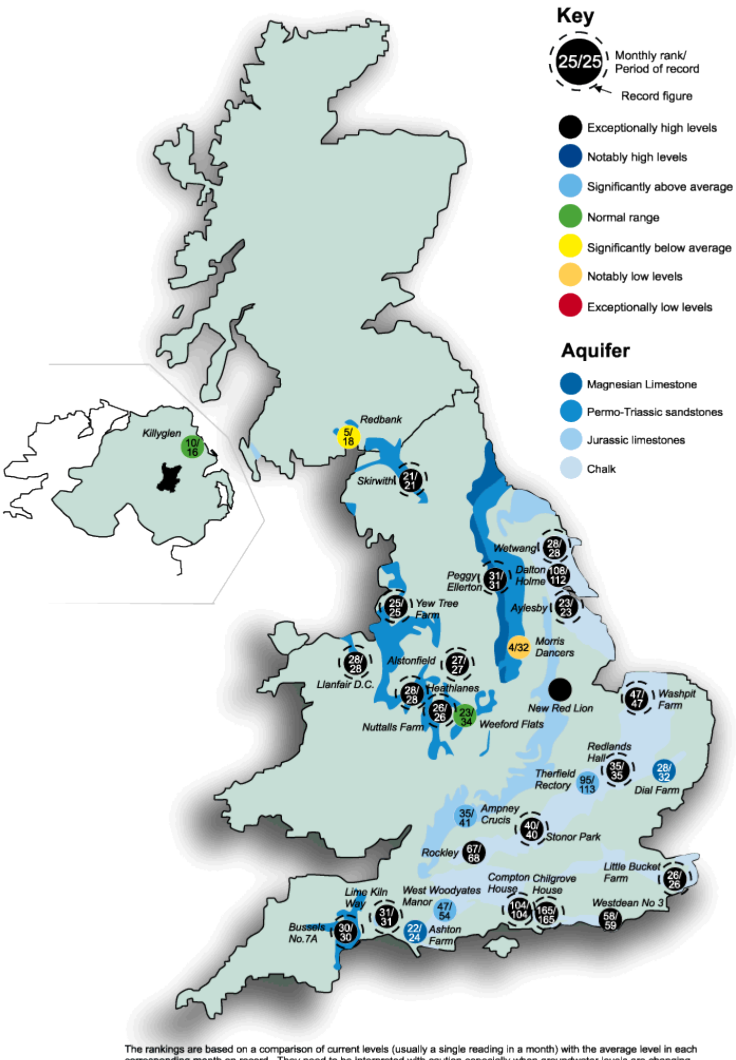


Figure 13 *(Contd.)*

recovery in groundwater levels across almost all aquifer units. Infiltration during the autumn was more than three times the average in many eastern Chalk outcrops and very notable water-table rises were reported from across the country. In the Carboniferous Limestone at Alstonefield, November levels were around 40 metres above the late summer levels and, at West Woodyates, levels in the Chalk rose 25 metres in 18 days (to the 10th November). At Chilgrove in the Chalk of the South Downs, the borehole began to overflow on the 8th November; in a groundwater level series from 1836 overflow periods are rare, and thought to be unprecedented in early November. By late December, many existing groundwater level maxima had been exceeded - see Figure 14. Record high levels were reported in most major and minor aquifers and record flows were reported from high level springs as the year ended.

Maximum and minimum groundwater levels recorded during 2000 (and early 2001) are compared with the corresponding long term extremes in Table 1. Around half the index wells and boreholes established new maximum levels over the six months from November 2000. The margins by which previous maxima were eclipsed underline the singular nature of the late-2000 recharge. At Compton, levels in the Chalk peaked at over four metres higher than the previous maximum in a record from 1894. In the older aquifers, Peggy Ellerton (Magnesian Limestone) and Heathlanes (Permo-Triassic sandstones) both exceeded their previous highest on record by significant margins (relative to the normal range of variation). For several index monitoring sites, the 2000 peak and the previous maxima are similar, in some cases (including Chilgrove) this is because the well or borehole has overflowed - this was a common occurrence in the late autumn and through the following winter, with many continuing to overflow for many weeks. In many wells - those in the eastern Chalk especially - groundwater levels continued to rise through the winter, establishing unprecedented maxima in the late winter/early spring of 2001. These maxima corresponded with exceptional outflow from high level springs and widespread and sustained groundwater flooding. Initial analyses based on long groundwater level records in the Chalk suggest that there has been no event of corresponding severity in the last 100 years at least.



The rankings are based on a comparison of current levels (usually a single reading in a month) with the average level in each corresponding month on record. They need to be interpreted with caution especially when groundwater levels are changing rapidly or when comparing wells with very different periods of record. Rankings omitted where they are considered misleading.

Figure 14 *The ranking of December 2000 groundwater levels for a selection of observational wells and boreholes.*

Data sources: Environment Agency/Scottish Environment Protection Agency/ Rivers Agency.

The majority of observation wells and boreholes for which data are held on the National Groundwater Level Archive monitor the natural variation in levels. However, in parts of the UK levels have been influenced, sometimes over very long periods, by pumping for water supply or other purposes. As a consequence, the local or regional water-table may become substantially depressed. For instance, contemporary levels at a number of boreholes in the Permo-Triassic sandstones of the Midlands are indicative of a significant regional decline. In London, increasing groundwater abstraction through the nineteenth and the first half of the twentieth centuries led to a 70-metre decline in groundwater levels in the Trafalgar Square borehole. Since the 1950s, a much reduced abstraction rate has resulted in a recovery of around 30 metres; levels rose by 1-2 metres a year through the 1990s but the rise during 2000 was more modest. Rising groundwater levels have also been reported from other conurbations; leakage from water mains is considered a significant factor in some cases. The implications of rising groundwater levels extend beyond the potential improvement in water resources that the rise represents. Groundwater quality may be adversely affected as levels approach the surface and a number of geotechnical problems may result, for instance the flooding of tunnels and foundations.

Table 1 *Groundwater levels in selected observation boreholes.*

Borehole Number	Site	Aquifer	Records Commence	Maximum levels		Minimum levels		Rise over winter 2000/01
				Pre-2000	2000/01	Pre-2000	2000/01	
SE94/5	Dalton Holme	CHALK	1889	23.82	22.34	9.64	15.01	7.33
SE95/6	Wetwang	CHALK	1971	35.15	37.37	16.66	20.06	17.30
TF81/2A	Washpit Farm	CHALK	1950	49.90	49.21	40.30	44.29	4.92
TL33/4	Therfield Rectory	CHALK	1883	99.05	96.57	70.69	74.23	22.3
TL44/12	Redlands Hall	CHALK	1963	54.50	56.25	32.29	38.33	17.90
SU17/57	Rockley	CHALK	1933	144.11	143.75	128.59	131.39	12.30
TR14/9	Little Bucket Farm	CHALK	1971	86.87	87.16	56.77	67.83	19.30
SU71/23	Compton House	CHALK	1894	68.75	73.37	27.64	33.67	39.70
SU81/1	Chilgrove House	CHALK	1836	77.19	77.18	33.46	41.32	35.80
TV59/7C	Westdean No.3	CHALK	1940	5.03	4.18	1.01	1.46	2.72
ST30/7	Lime Kiln Way	UGS	1969	126.48	127.08	123.70	125.48	1.59
SY68/34	Ashton Farm	CHALK	1974	71.48	71.52	63.10	65.05	6.47
SU01/5B	West Woodyates Manor	CHALK	1942	109.40	108.12	67.62	71.55	36.50
ID30/1	Killyglen (NI)	CHALK	1985	119.96	118.94	112.60	113.07	5.87
TA10/63	Aylesby	CHALK	1976	22.12	21.71	5.65	13.85	7.86
TM15/11	Dial Farm	CHALK	1968	26.38	26.14	24.61	25.59	0.55
SU78/45	Stonor Park	CHALK	1961	87.39	92.14	61.53	72.30	19.80
TF03/37	New Red Lion	LLST	1964	23.69	21.63	3.29	12.45	9.18
SP00/62	Ampney Crucis	MJUR	1958	103.45	103.20	97.38	99.94	3.26
NX97/1	Redbank	PTS	1981	9.45	8.45	7.13	7.22	1.09
SD41/32	Yew Tree Farm	PTS	1972	14.01	14.2	8.43	13.75	0.44
NY63/2	Skirwith	PTS	1978	131.70	131.80	129.35	130.27	1.53
SJ15/13	Llanfair D.C	PTS	1972	80.63	81.12	78.67	80.01	1.11
SK67/17	Morris Dancers	PTS	1969	33.58	31.93	31.40	31.68	0.25
SJ62/112	Heathlanes	PTS	1971	63.41	64.21	60.22	62.16	2.05
SX99/37	Bussells No.7A	PTS	1971	25.28	25.26	22.90	23.67	1.59
NZ22/22	Rusheyford NE	MGLST	1967	77.10	77.90	64.77	76.40	1.50
SE43/9	Peggy Ellerton	MGLST	1968	37.39	37.75	31.10	36.49	1.26
SK15/16	Alstonefield	CLST	1974	216.18	217.53	174.22	171.85	45.60
SK10/9	Weeford Flats	PTS	1996	91.76	91.65	88.61	89.57	2.08
SK00/41	Nuttall Farm	PTS	1974	130.72	131.55	127.79	130.71	0.84

Location Map

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