UK Hydrological Review 2001

2nd Edition

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

2001

UK HYDROLOGICAL REVIEW

This Hydrological Review, which also provides an overview of water resources status throughout 2001, is a reformatted version of the original commentary released as a web report in 2002. 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 2001

2001 Summary

Though considerably less outstanding than the previous year, 2001 was still very noteworthy in hydrological terms. Like its predecessor, 2001 was a warm year but river flow and aquifer recharge patterns were markedly different. The differences reflect a return to a spatially more typical distribution of rainfall during 2001, but combined with a very uneven distribution through the seasons. The early months were exceptionally wet in southern Britain but notable rainfall deficiencies developed in some western parts of the UK over the latter half of the year and, nationally, there was a very dry conclusion to 2001.

Throughout most of southern Britain the exceptionally wet phase that began during the latter half of 1997 culminated over the last four months of 2000 - but sustained and heavy rainfall continued well into the spring of 2001. Existing maximum recorded rainfall accumulations (over a wide range of months) were eclipsed for England and Wales as a whole. A major contributory factor was the unusually southerly tracks followed by many Atlantic frontal systems - producing outstanding rainfall totals over most of southern Britain whilst, concurrently, modest rainfall deficiencies developed in parts of Scotland. For many English catchments rainfall totals over periods of three to eight months (within the September 2000 - April 2001 timespan) were without precedent. Commonly they were considerably greater than previous maxima over the period for which river flow or groundwater level data are available.

Since 1987, the annual mean Central England Temperature[1] has fallen below the 1961-90 average only once (in 1996). 2001 added to the cluster of recent warm years. Partly as a consequence, potential evaporation losses for Britain as a whole were above average, notably so in parts of eastern England. Actual evaporation losses - which normally fall short of the corresponding potential evaporation losses due to the inhibiting effect of limited soil moisture in the late summer and early autumn - were generally in the normal range. Much of the English Lowlands provided an important exception - here sustained rainfall during July-September restricted the period over which substantial soil moisture deficits were maintained; as a result actual evaporation losses for 2001 were close to the highest on record in many areas.

Nationally, water resources were exceptionally high during the late winter of 2000/01 - unprecedented if reservoir and groundwater storage are considered together. During the early months of 2001, some drawdown of major reservoirs was necessary to provide increased flood alleviation capability. Nonetheless, overall reservoir stocks for England and Wales remained above the monthly average throughout the year (Figure 1). Stocks decreased briskly through the early summer but, more significantly for the water resources outlook, a further decline during November and October - when reservoir levels are normally rising - resulted in overall stocks falling close to the monthly average at the beginning of 2002 - having remained above average since the autumn of 1997 (Figure 2).

A guide to the variation in annual runoff for England and Wales, Scotland and Northern Ireland - expressed

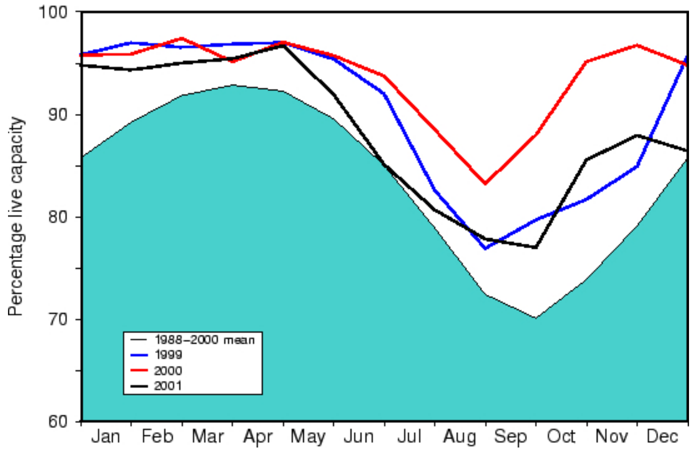


Figure 1 *Reservoir stocks in 2001.*

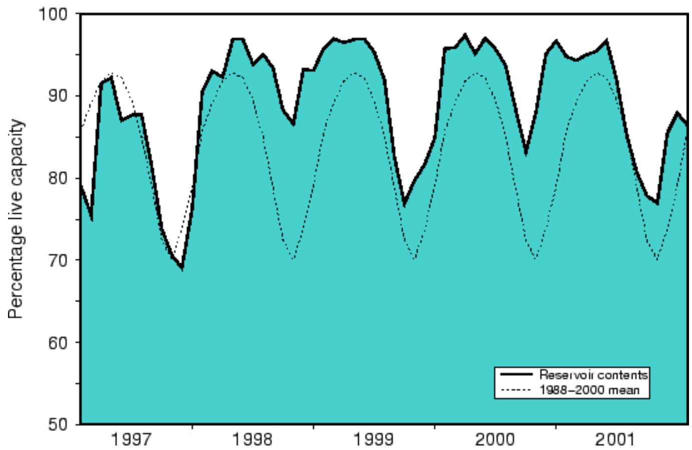


Figure 2 *Reservoir stocks in 1997-2001.*

as percentage departures from the long term mean - is shown on Figure 3; the percentage departures are based on outflows from representative networks of major river basins. For England and Wales as a whole, runoff exceeded the average for the fourth successive year; the 1997-2001 runoff total significantly exceeds that for any other four-year sequence in the 41-year national series. Well above average runoff also characterised Scotland over the 1998-2000 period but the runoff total for 2001 was considerably below average - a very uncommon occurrence over the last 25 years. In Northern Ireland, a province-wide gauging

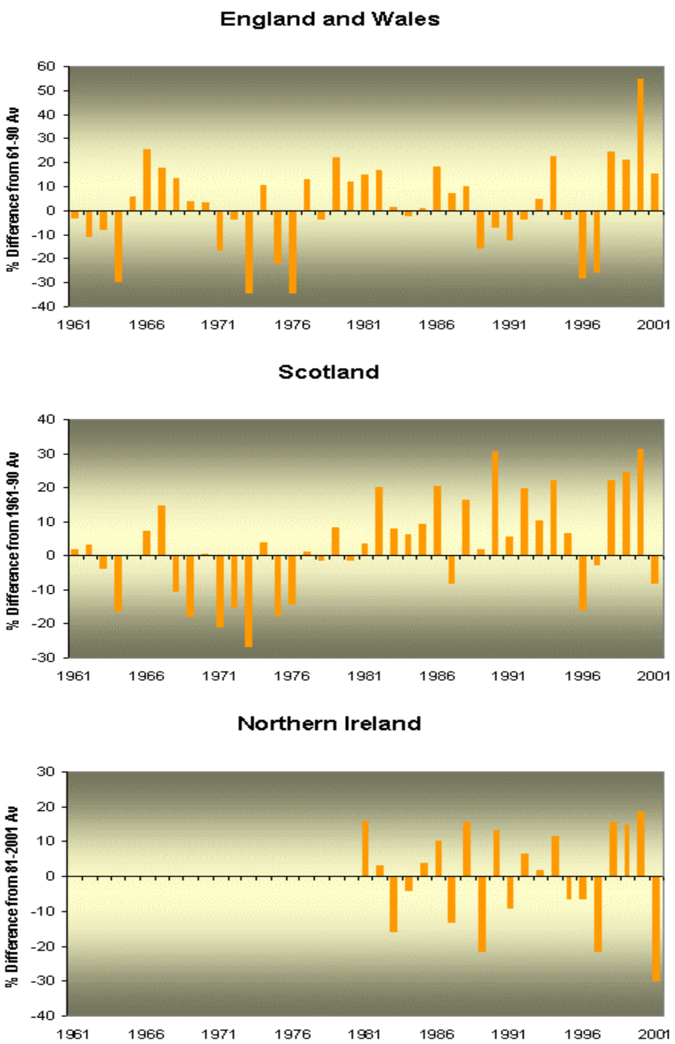


Figure 3 *Runoff 1961-2001.*

station network has operated only since the mid 1970s. In the context of the last 20 years, the 2001 runoff was around 30% below average, establishing a new annual minimum for Northern Ireland. The contrasting runoff patterns at the national scale were reflected in substantial regional and catchment variability in 2001 runoff totals.

Relative to 2000, the frequency of flood events was much reduced in 2001 - but overbank flows were still common during the late winter and early spring, particularly in permeable catchments across southern England. Over this period, the recorded range of flows in springs and groundwater-fed rivers was extended over wide areas. In permeable catchments, river flows remained at seasonally high levels throughout the summer. Flows in rivers draining impermeable catchments however were characterised by steep recessions from the late spring, as a result summer flows generally fell into the normal range. Following heavy early autumn rainfall, most catchments were again saturated by late October and many were vulnerable to further significant rainfall. The risk of a repetition of the widespread floodplain inundations in the autumn of 2000 remained high until mid-November. Thereafter a sustained dry spell, extending over 10 weeks in some areas, triggered lengthy recessions in the west and north, and stalled the seasonal recovery in spring-fed southern and eastern rivers. By year-end, depressed river flows characterised many responsive catchments in western and northern Britain, and parts of Northern Ireland also.

Available evidence, long-term rainfall records in particular, suggest that the magnitude of groundwater replenishment over the eight months beginning in September 2000 has no close parallel throughout the period over which routine groundwater level measurements have been taken (over 150 years in a few localities). Late-2000 and early-2001 rainfall was exceptional across most aquifer outcrop areas but the most outstanding anomalies were in the South-East where some areas recorded around twice the 1961-90 average rainfall for the winter half year - generally well above previous maxima. Correspondingly, dramatic groundwater level rises over the last 10 weeks of 2000 heralded an unprecedented period of sustained high groundwater levels. Levels remained above previous maxima for extended periods during the first five months of 2001 and sustained ‘clearwater’ flooding was very widely reported. The lowland stream network extended high into the headwaters of many ‘dry’ valleys and the extent of the groundwater flooding almost certainly exceeded any similar episode in the instrumented era. Groundwater levels remained well above average in the less fissured (and less responsive) aquifers for very lengthy periods - exceeding previous maxima for over four months in parts of the Chalk, and longer in many Permo-Triassic sandstones outcrops. Rapid drainage from high level springs produced a steep water-table decline through the late spring and summer of 2001 but groundwater levels remained above, or within, the normal range until the late autumn in most regions. Thereafter the very modest nature of the seasonal recovery in the autumn left groundwater levels in most Chalk wells and boreholes around the seasonal average at year-end; generally levels remained very high in the Permo-Triassic sandstones.

2001 saw a continuation of the hydrological volatility that has been a feature of the recent past. The protracted droughts of the early and mid-1990s have been succeeded by a sustained wet period that culminated in the exceptional flooding of 2000/01. The last 10 years have witnessed an extension in the range of recorded runoff and recharge rates in many parts of the UK. However, the significance of this extension needs to be considered alongside the limited record length (typically <25 years) of most UK hydrometric datasets, and the broad stability that typifies long river flow and groundwater level series unaffected by artificial influences. Hydrological conditions in the recent past show some consistency with favoured climate change scenarios, e.g. the high temperatures and the cluster of wet winters. However, in a warmer world, hydrological patterns in the UK will continue to reflect the complex interaction of rainfall, evaporation and soil moisture conditions (as well as land use changes and other more direct artificial influences on runoff and recharge patterns). There remains considerable uncertainty regarding climate change impacts - future rainfall patterns especially - at the regional and catchment scales. As yet there is very limited evidence of any compelling long term hydrological trends in the UK - careful monitoring will continue to be essential to identify and interpret any significant climate-driven signals.

Rainfall

The year in brief

The UK rainfall total for 2001 was modestly below average (see Table 1) but spatial and temporal variations in rainfall patterns throughout the year were very marked. Provisional data indicate that 2001 was the third driest year on record for Northern Ireland (in a series from 1900) and some catchments in western Scotland reported less than 75% of average annual rainfall. By contrast, large parts of the English Lowlands, East Anglia in particular, reported well above average rainfall (Figure 4) - for the fourth successive year in many catchments. Counterbalancing below average rainfall to the west and north resulted in the 2001 rainfall total for England and Wales being close to the long term mean.

January excepted, the early months of 2001 - as during the last quarter of 2000 - were characterised by a remarkable moderation in the normal north-west to south-east rainfall gradient across the country. Within a few timespans the gradient was reversed, for example the January-April rainfall total for the Environment Agency's Southern Region were significantly greater than that for the Highland Region in Scotland. Thus, over a period when notable rainfall deficiencies were developing in parts of Scotland and Northern Ireland, many new rainfall records were being established across most of southern Britain.

After a respite in January, most Atlantic frontal systems continued to follow an unusually southerly track. The frequency and intensity of these systems contributed to the highest January-April rainfall for 50 years for England and Wales. More remarkably, the continuation of the exceptionally wet weather, which was a feature of late-2000, resulted in new maximum n-month rainfall totals being established for all timeframes between 5 and 32 months (15-17 months excepted); most of these outstandingly wet periods terminate in the first half of 2001. Generally the margin by which previous maxima were eclipsed is modest, but the length of the 2000/01 wet episode is very exceptional.

From late April, the synoptic pattern changed, rain-bearing frontal systems began to follow more familiar routes and below average rainfall characterised much of the remainder of the year. Significant rainfall deficiencies developed in most regions through the late spring and summer, culminating in exceptionally dry conditions during November and December - when rainfall was less than half the average in much of southern England. At year-end, rainfall deficiencies were of most water resources significance in the South-West which registered its driest May-December since 1921 in some catchments.

Rainfall - through the year

In contrast to the cyclonic conditions which dominated the last four months of 2000, the westward extension of a European high pressure cell produced colder, more settled conditions in January 2001. Notwithstanding significant snowfall in northern Britain, regional precipitation totals (the South-East aside), were mostly below average. However, the contrast in synoptic patterns between the north and south of the country in late 2000 re-asserted itself in February when some eastern catchments registered more than twice the average rainfall.

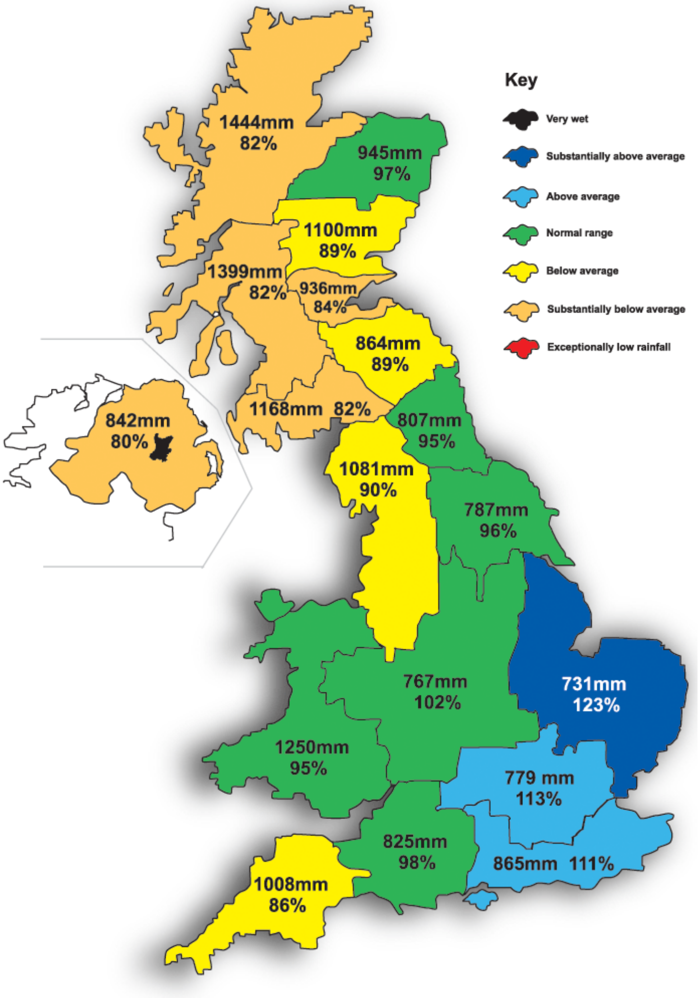
March was again very wet in the English Lowlands whilst rainfall totals were mostly <70% of average in western Scotland and Northern Ireland. Parts of northern Scotland were again dry in April but most regions of the UK recorded well above average rainfall. For the third time since 1997, April was notably wet across England and Wales. More remarkably, rainfall over the eight months ending in April 2001 exceeded the annual average by wide margins across most of southern Britain (Figure 5). May was a warm and, in most areas, a dry month - a few coastal districts in the North-East recorded less than 20% of the 1961-90 average rainfall and regional totals were mostly in the 40-75% range. More significantly, several catchments in the Scottish Highlands reported below average rainfall for the seventh successive month. Across much of Scotland, it was the driest January-May period in at least 20 years.

In most regions relatively settled weather continued into the early summer as frontal systems tended to follow tracks remote from the English Lowlands. Correspondingly, June rainfall totals were substantially below average in much of southern Britain. July weather patterns were much more variable - heatwave conditions alternating with more autumnal interludes. Thunderstorms, some of violent intensity, were common; on the 17/18th a precipitation total of 99mm in 15 hours was recorded at Keyworth (Staffs) whilst

Table 1 *2001 Rainfall in mm as a % of the 1961-90 average.*

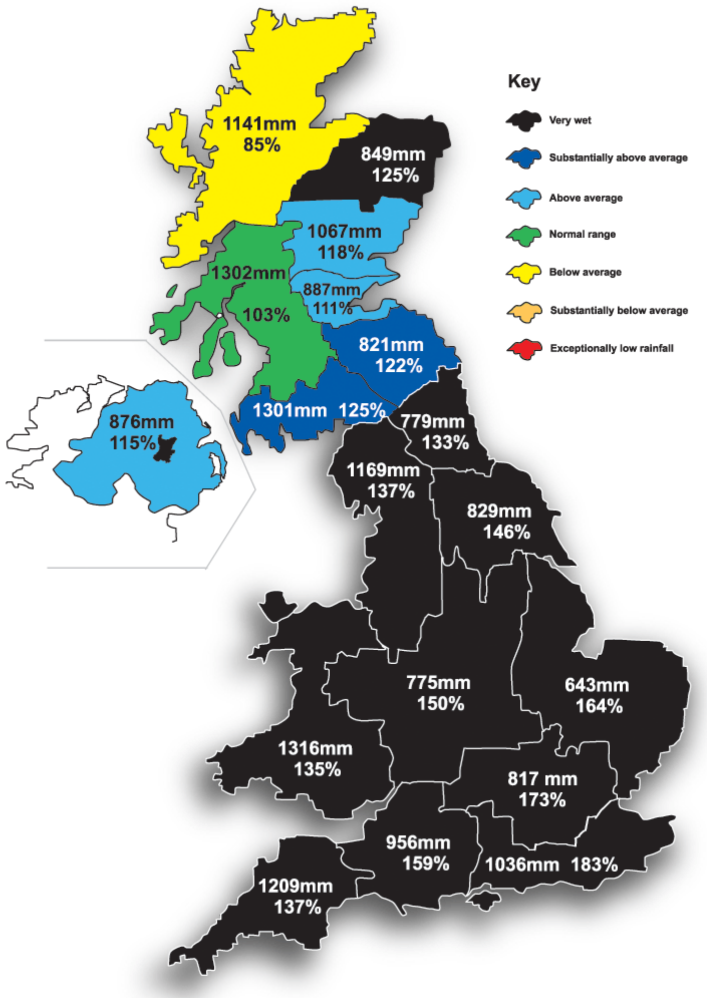
Data source: UK Met Office.

2001		J	F	M	A	M	J	J	A	S	O	N	D	Year	Oct-Mar 2000/01	Apr-Sep 2001
United Kingdom	mm	76	94	82	86	42	55	77	91	80	155	89	65	991	764	430
	%	69	124	92	132	58	77	105	101	81	140	81	57	92	126	91
England and Wales	mm	73	93	89	95	42	41	68	80	77	130	67	44	899	741	403
	%	83	148	123	158	65	62	110	106	100	153	75	46	100	151	100
Scotland	mm	86	102	73	70	40	82	97	109	91	210	134	103	1196	827	489
	%	57	100	59	92	47	95	103	93	64	134	89	68	83	99	81
Northern Ireland	mm	64	65	65	75	49	64	59	100	50	107	68	77	842	672	397
	%	57	83	74	117	69	90	89	109	51	94	66	74	80	113	86
North West	mm	72	110	61	113	56	56	65	98	123	166	92	70	1081	885	511
	%	59	141	64	159	74	69	76	92	107	129	75	57	90	132	96
Northumbrian	mm	47	100	52	81	16	64	57	70	91	105	61	63	807	586	379
	%	56	169	74	145	26	106	88	86	124	138	71	78	95	129	95
Severn Trent	mm	46	75	65	93	60	34	71	70	60	110	49	34	767	574	388
	%	66	139	107	169	102	57	134	104	94	172	69	44	102	144	109
Yorkshire	mm	44	93	52	94	33	49	46	79	94	110	48	47	787	603	395
	%	56	160	76	158	55	82	77	107	139	150	60	56	96	137	104
Anglian	mm	48	74	74	76	41	37	75	69	81	82	49	25	731	486	377
	%	97	201	158	164	85	72	152	125	165	161	84	46	123	163	127
Thames	mm	72	83	95	81	39	30	53	79	61	119	42	25	779	641	343
	%	113	184	170	162	69	55	108	137	103	191	65	35	113	177	105
Southern	mm	104	102	122	74	26	21	50	78	84	137	40	28	865	852	332
	%	130	189	194	139	48	38	104	137	121	171	47	34	111	192	99
Wessex	mm	94	77	115	82	31	27	68	75	37	138	51	31	825	766	319
	%	108	119	164	154	51	47	132	113	51	175	61	33	98	161	88
South West	mm	125	81	141	107	26	40	79	64	45	151	95	53	1008	964	362
	%	91	80	142	155	37	58	115	77	49	130	76	38	86	134	79
Welsh	mm	90	114	118	132	62	43	95	119	81	202	126	69	1250	1026	532
	%	63	118	110	165	75	55	123	118	70	148	89	45	95	132	100
Highland	mm	93	105	75	82	63	107	109	116	107	254	187	148	1444	949	583
	%	49	83	46	90	68	109	103	91	62	128	92	75	82	88	85
North East	mm	70	89	83	52	32	54	76	100	82	150	77	81	945	687	395
	%	70	138	107	86	46	82	104	114	94	155	77	87	97	129	89
Tay	mm	104	128	84	57	36	66	88	105	70	214	84	64	1100	847	422
	%	72	135	77	93	43	90	114	112	61	164	70	50	89	117	84
Forth	mm	79	91	70	65	28	70	86	92	62	157	82	55	936	667	403
	%	67	115	74	110	38	101	115	98	57	136	73	50	84	106	84
Clyde	mm	124	101	81	87	40	105	123	142	95	239	163	99	1399	993	592
	%	66	86	55	103	44	113	113	106	53	124	91	55	82	99	86
Tweed	mm	60	93	64	74	22	74	74	80	69	132	67	56	864	617	393
	%	60	139	81	129	31	114	102	91	77	139	72	60	89	117	89
Solway	mm	97	105	75	100	37	77	93	97	99	202	112	76	1168	997	502
	%	62	104	64	129	44	92	103	81	69	128	78	51	82	121	84
Western Isles; Orkney and Shetland	mm	79	78	65	61	38	66	81	92	95	167	132	119	1073	701	433
	%	63	93	64	98	64	108	116	107	79	124	100	93	92	99	94



The rainfall figures are provisional; revised figures will be posted subsequently.

Figure 4 *2001 regional rainfall totals / %.*



The rainfall figures are provisional for all regions; revised figures will be posted subsequently

Figure 5 *Regional rainfall, October 2000 - April 2001.*

Weybourne (Norfolk) registered 40.1mm in three hours. As a consequence, spatial variations in monthly precipitation totals were large. A few catchments in western Scotland reported their first above average monthly rainfall total of the year - but accumulated deficiencies remained substantial. Provisional data indicate that Scotland and Northern Ireland registered their lowest January-July rainfall total since 1955 and 1953 respectively.

August continued the July theme with convective precipitation contributing a significant proportion of the monthly total; a 55.6mm storm total was recorded at Northolt (west London) in 12 hours on the 9th - including 34mm in less than an hour. Again, spatial coherence in monthly precipitation amounts was limited but, regionally, most August totals were in the 80-120% range. Summer (June-August) rainfall totals were also close to the 1961-90 average, with most regions registering within 10% of the mean - but many catchments in the south-west and north-west of England were significantly drier.

Rainfall in September was very close to the 1961-90 average for England and Wales as a whole - an unexceptional end to the wettest water-year (October-September) since 1876/77. The September rainfall strongly favoured eastern regions, much of northern and western Britain - and Northern Ireland - had a relatively dry month. Rainfall deficiencies continued to build in many western catchments. In the South-West, water was shipped to Lundy to replenish depleted stocks and the regional May-September rainfall total was similar to that recorded during the 1989 drought. Deficiencies extended over a longer period in Northern Ireland where rainfall for the first nine months of 2001 was the third lowest in a series from 1900.

Weather patterns became very much more unsettled in the final week of September. On the 25th, a rainfall total of 65mm in just over an hour was reported for Oulton (Norfolk) - significant localised flooding resulted, some the result of rapid melting of large hail drifts. The passage of a very active frontal system on the 30th - which resulted in a 52.5mm rainfall total in 24 hrs at Vyrnwy (north Wales) heralded a notably unsettled October with several exceptionally wet interludes. In East Anglia, many areas registered around the monthly average rainfall during the three days beginning on the19th; 90.4mm was recorded in 18 hours at Cambridge (the corresponding return period exceeds

100 years); a similar total was reported for Stansted Mountfitchet (Essex) over the 20/21st. Britain as whole registered its third notably wet October in four years (both 2000 and 1998 produced substantially higher rainfall totals).

With soils at, or close to, saturation across much of the country in early November, the subsequent dominance of anticyclonic conditions was very helpful in moderating the flood risk. The low frequency of Atlantic frontal systems was reflected in the rainfall totals - England and Wales recorded its driest November since 1989. The high pressure intensified in December, diverting many early-winter Atlantic low pressure systems to the north of the UK. Temperatures declined steeply and a significant proportion of the December precipitation in northern Britain was as snow; some particularly heavy falls occurred in north-east Scotland. Nonetheless, monthly precipitation totals were modest across most of the country - well below 50% in much of southern Britain. Provisional rainfall figures indicate that the November-December precipitation total for the UK was amongst the three lowest since 1945; in parts of the South-East it was the second driest end to the year since 1933 (Figure 6).

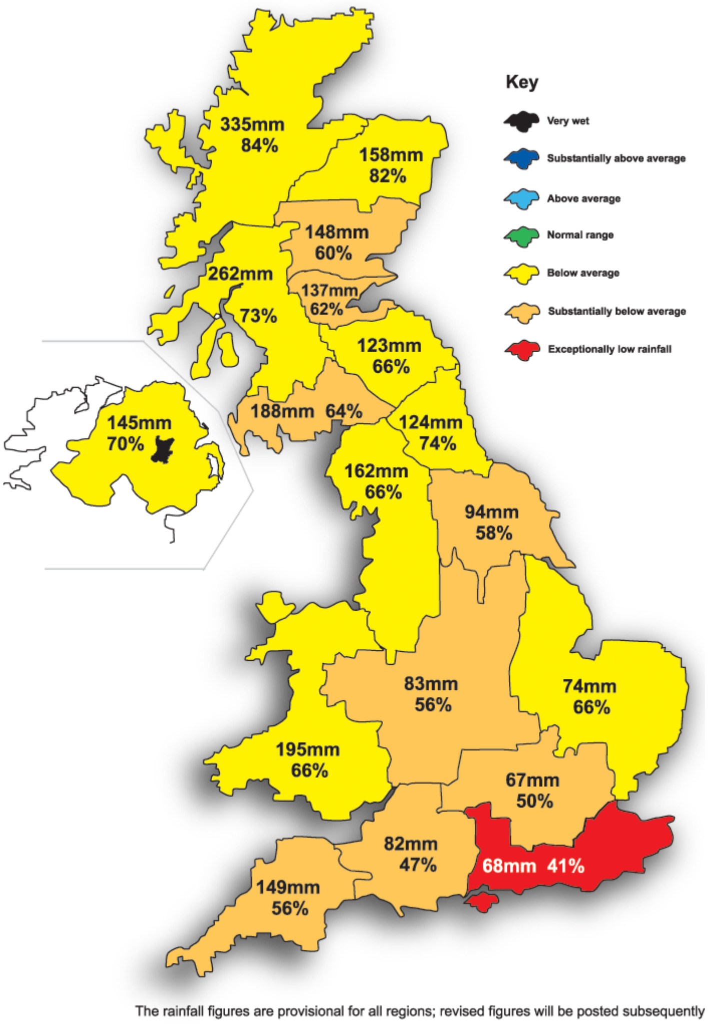


Figure 6 *Regional rainfall, November - December 2001.*

Evaporation and Soil Moisture Deficits

Potential and actual evaporation losses

2001 was another warm year across the UK; the annual mean Central England Temperature exceeded the 1961-90 average by around 0.7°C; May, July and August were particularly warm and October remarkably mild. Correspondingly - and in common with most recent years - potential evaporation (PE) totals were above average throughout much of the UK. Annual totals, computed using the Met Office Rainfall and Evaporation Calculation System (MORECS) methodology, and assuming a grass cover, displayed the normal decline from southern and eastern England - where values greater than 630mm were common - to the Scottish Highlands where 400-450mm totals were more typical (Figure 7). Relative to the 1961-90 average, anomalies were modest but a few coastal districts in eastern England registered more than 20% above average and, generally, the highest positive anomalies were in the English Lowlands. By contrast PE losses fell a little below average throughout parts of the Scottish Highlands.

Annual actual evaporation (AE) totals (again assuming a grass cover) were mostly in the 450-600mm range (Figure 8), with the higher totals often associated with coastal localities where wind can be a significant factor. Actual evaporation losses for 2001 were similar to corresponding PE totals in the wetter catchments in northern and western Britain where only modest soil moisture deficits were established in the summer (see below). In these regions annual AE losses were mostly close to the long term average albeit appreciably below average in the western Highlands. As usual however, AE totals fell significantly below PE losses across a substantial proportion of the English Lowlands - the differences exceeded 100mm in some parts of the east Midlands (e.g. the lower Trent basin). By contrast, AE totals were well above average in parts of southern England and East Anglia; new maximum annual AE totals were established for a few MORECS squares (e.g. in Norfolk). For much of East Anglia, above average annual AE totals have been registered in each of the last five years - losses over this period have been significantly higher than for any other 5-year sequence in the 1961-2001 MORECS series. This is a reflection of the limited period over which transpiration losses have been inhibited by very dry soil conditions.

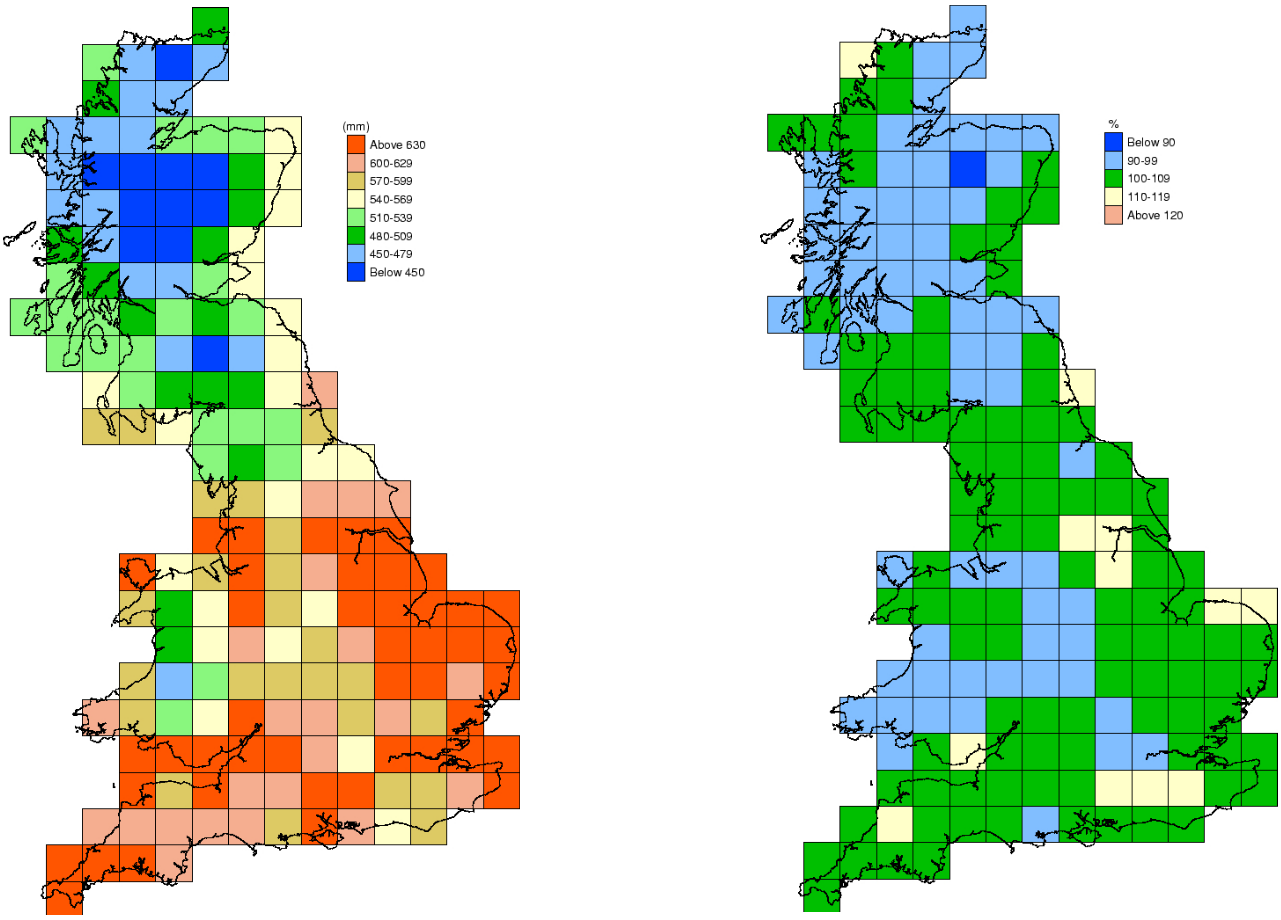


Figure 7 *Potential evaporation totals for 2001 in mm and as a percentage of the 1961-90 average.*

Data source: MORECS.

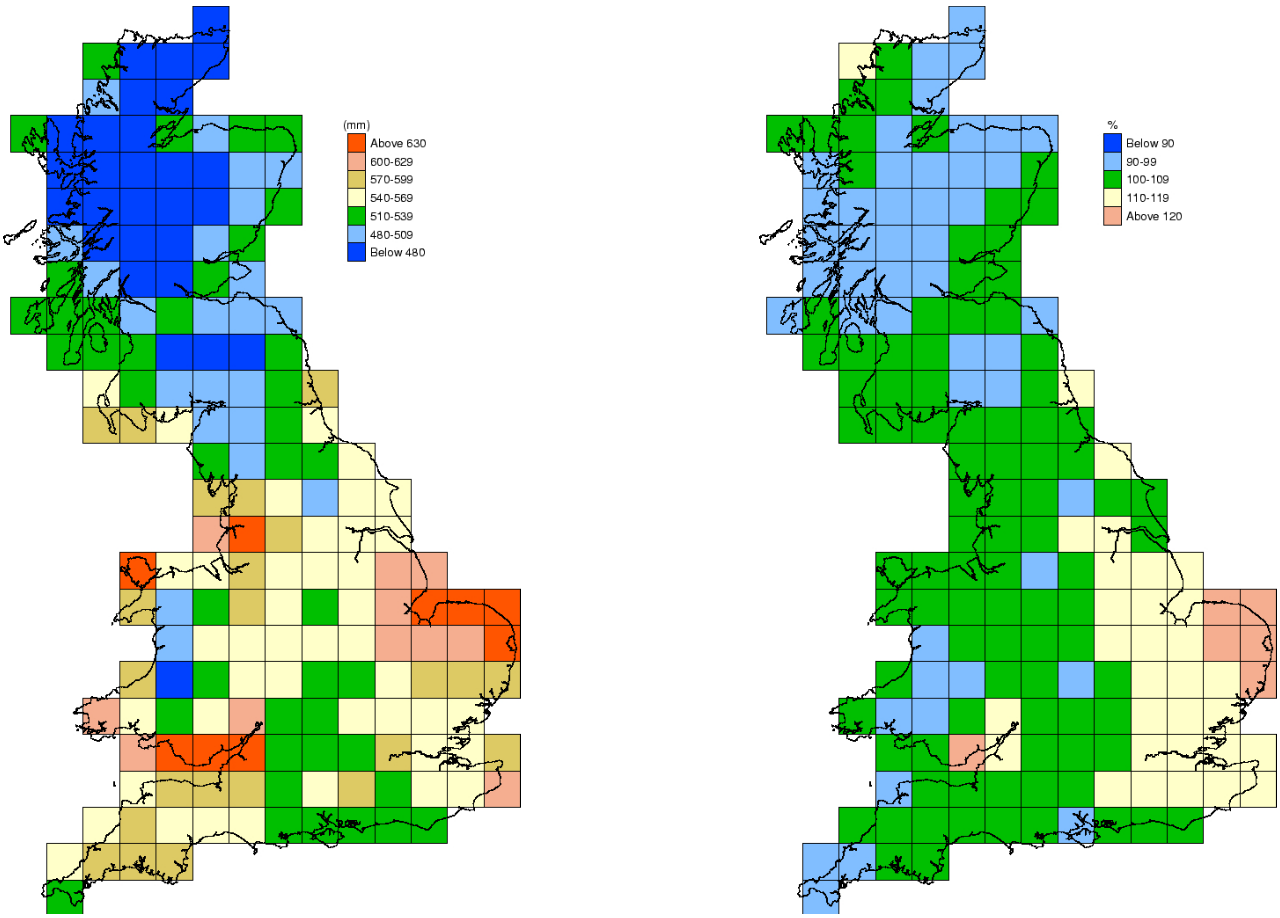


Figure 8 *Actual evaporation totals for 2001 in mm and as a percentage of the 1961-90 average.*

Data source: MORECS.

Soil Moisture Deficits

In a typical year, the ability of transpiration to proceed at its potential rate is reduced from the early spring, as a result of drying soil conditions, the ability of the vegetation to take up water and the measures plants take to restrict moisture loss under such circumstances. Thus in the absence of favourable soil moisture conditions actual evaporation rates fall below the PE rate, appreciably so in dry years. Given normal rainfall, the accelerating evaporation demand during the spring leads to a progressive drying of the soil profile and the creation of what is termed a 'soil moisture deficit' (smd), consequently surface runoff and infiltration to aquifers is greatly reduced. When plant activity and evaporation rates slacken in the autumn, rainfall wets-up the soil profile and, as saturation is approached, runoff rates increase and aquifer replenishment commences again.

The development and decay of soil moisture deficits over the 1997-2001 period is illustrated on Figure 9 for six representative MORECS squares; monthly PE and AE losses are also shown. The smd data are end-of-month values and assume a grass cover. In western Scotland (square 55) and central Wales (134) smds increased briskly through the late spring and early summer but maximum deficits were within the normal range - and too low to significantly constrain transpiration losses; the PE and AE traces in Figure 9 are therefore coincident. As usual, peak smds in the English Lowlands were much higher - typically twice as high - as those characterising much of northern Britain. As a result AE losses fell appreciably below the corresponding PE values throughout much of the summer, and longer in some eastern areas. Maximum smds during 2001 generally occurred in the late summer and, again, were mostly well within the normal range. Deficits decreased smartly through late September and October across much of the country and soils in most catchments were approaching saturation by the late autumn. The steep decline in smds triggered an early onset of the seasonal recovery in river flows and increased the likelihood of a second successive extended groundwater recharge season. However, the notably dry end to the year caused the seasonal hydrological recoveries to stall and, in large parts of eastern England, modest soil moisture deficits were carried over into 2002.

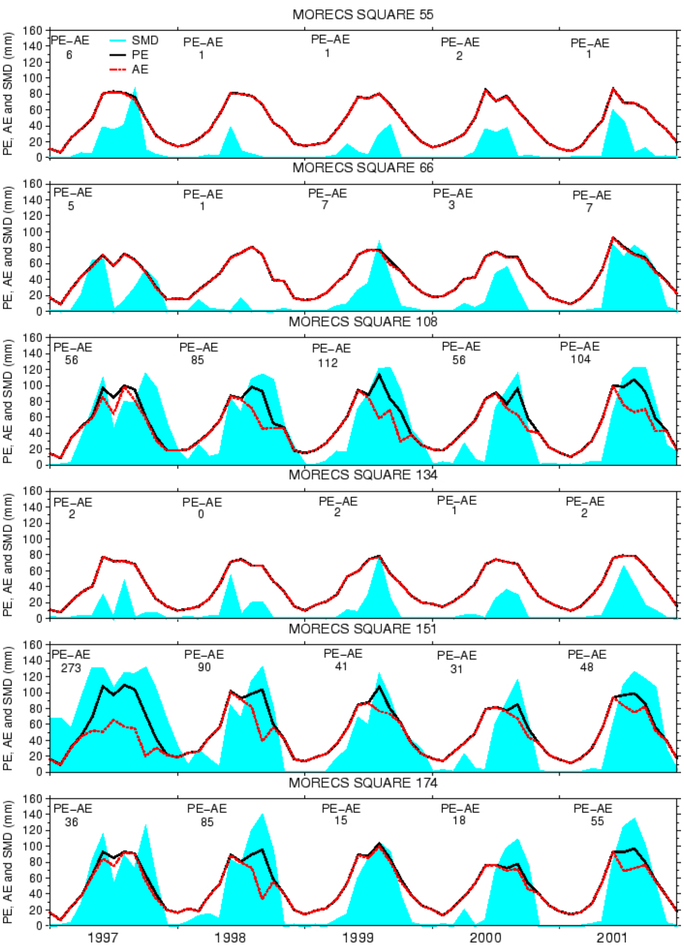


Figure 9a *The variation in potential evaporation, actual evaporation and soil moisture deficits for six MORECS squares 1997-2001.*

Data source: MORECS.

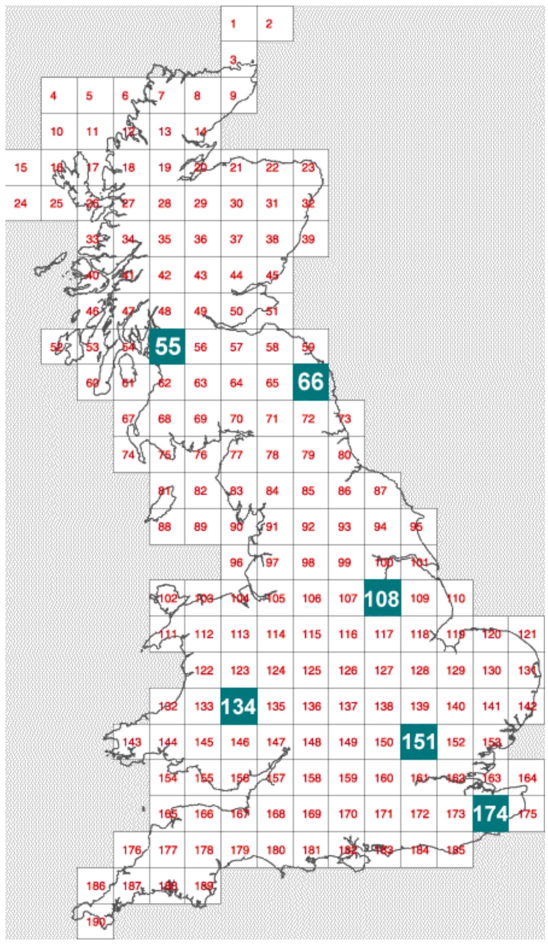
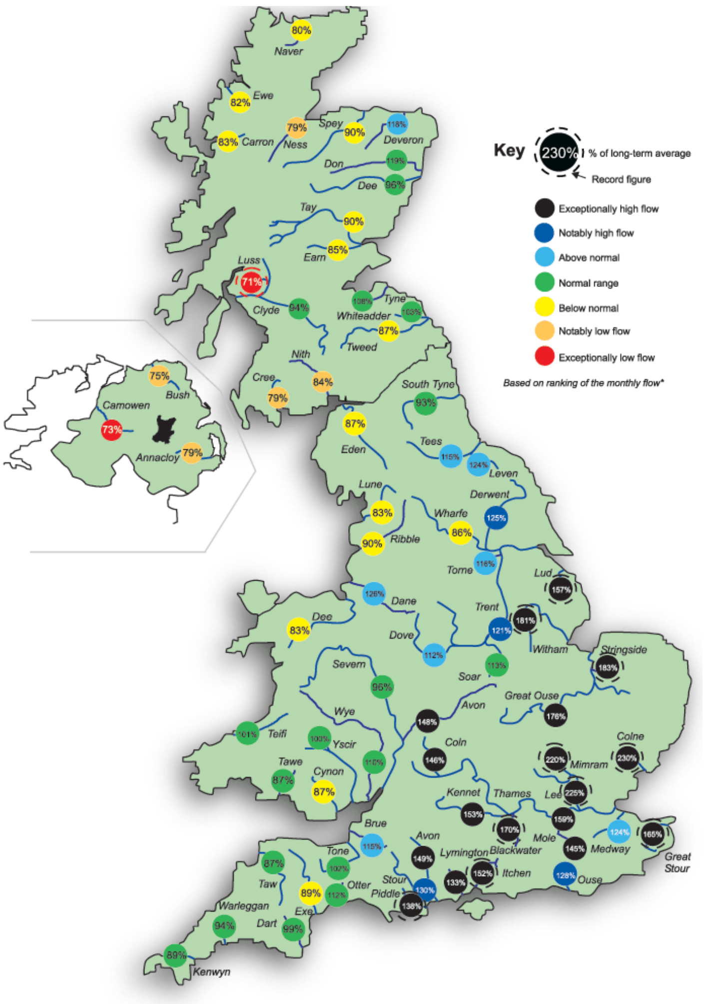


Figure 9b *MORECS Location Map: the location of the 40km squares and their associated reference numbers.*

River Flows

The year in brief

2001 was the fourth successive year for which runoff from the UK was above average; but the 1961-90 mean was only marginally exceeded, and regional differences in annual runoff anomalies were substantial. The influence of catchment geology on river flow patterns was particularly evident during 2001. Throughout most western and northern regions, where impermeable catchments predominate, river flows were well below average for the year as a whole. Runoff deficiencies were greatest in parts of Northern Ireland and western Scotland where, for example, the River Luss established a new annual minimum runoff total. By contrast, rivers supported mainly by groundwater - which are concentrated in eastern, central and southern England - registered very high annual average flows, (Figure 10). This was in part a result of the lagged response to the unprecedented rates of aquifer recharge over the October-December 2000 period (but heavy recharge continued into the early spring of 2001). Although river flow recessions were well established by the end of the year, many rivers registered their highest annual runoff on record - examples included the Lud, Itchen, Great Stour and Lee, the latter in a 123-year record. For many of these rivers, the 2000 runoff total ranks second highest and their high flow regimes have been substantially redefined over the recent past.



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

Figure 10 *January - December runoff map (index stations).*

Daily flow hydrographs for 20 index gauging stations throughout the UK are shown in Figure 11; the 2001 hydrographs are illustrated by the solid trace and the shaded envelopes illustrate the maximum and minimum daily flows over the preceding record. In Scotland, daily flows remained within the normal range throughout the year in most catchments. But late spring flows were significantly below average over wide areas; in some western catchments minimum flows for the year were registered in May or June. The summer recessions were regularly punctuated by significant spates but the highest flow rates in 2001 commonly occurred in October. As in 2000, steep recessions became established in impermeable catchments towards the end of the year - when flows in the Tay, for example, approached its previous end-of-year minima. In Northern Ireland flows were also depressed at year-end; the Annacloy established a new end-of-year minimum daily flow. These seasonally depressed runoff rates contrasted with the widespread spate conditions which characterised the beginning of the year.

Most English lowland rivers were characterised by sustained high flows until well into the spring of 2001. High flows were most persistent in spring-fed rivers many of which recorded remarkably high flows throughout the first six months of the year. Runoff for the River Mimram over the February-April period in 2001 was around 40% greater than for any pre-2000 four-month sequence in a 50-year record. Similarly, flows in the Ewelme Brook, which drains the scarp slope of the Chilterns, exceeded previous maxima by a very wide margin during the late winter and early spring. The singular nature of this runoff episode is confirmed by the flow record for the Wendover Springs (also in the Chilterns) which provides a unique insight into spring flow variability through the mid- and late-nineteenth century; no flows of a similar magnitude to those experienced in the spring of 2001 have been recorded in an (incomplete) flow series which begins in 1841.

The exceptional spring flows in rivers draining permeable catchments were primarily a response to extreme recharge over the preceding autumn and winter, but in many areas also reflect above average recharge through the previous three winters (see 'Groundwater'). In rivers reliant primarily on baseflow, the 2001 recessions began late, and often from unprecedented flow rates. Flows generally remained above average into the autumn but the seasonal recovery - which began in

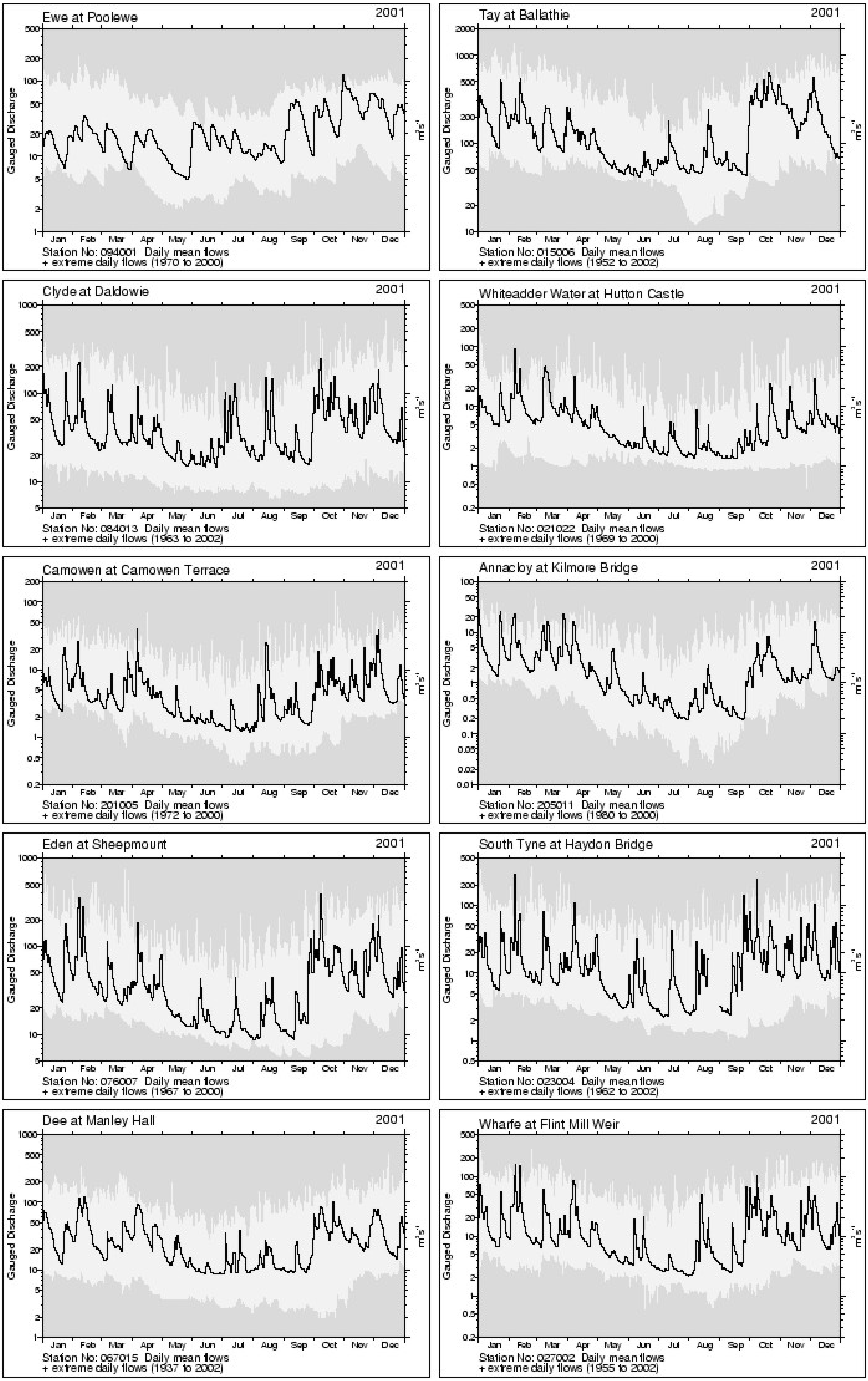


Figure 11 *Daily river flow hydrographs for 2001.*

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

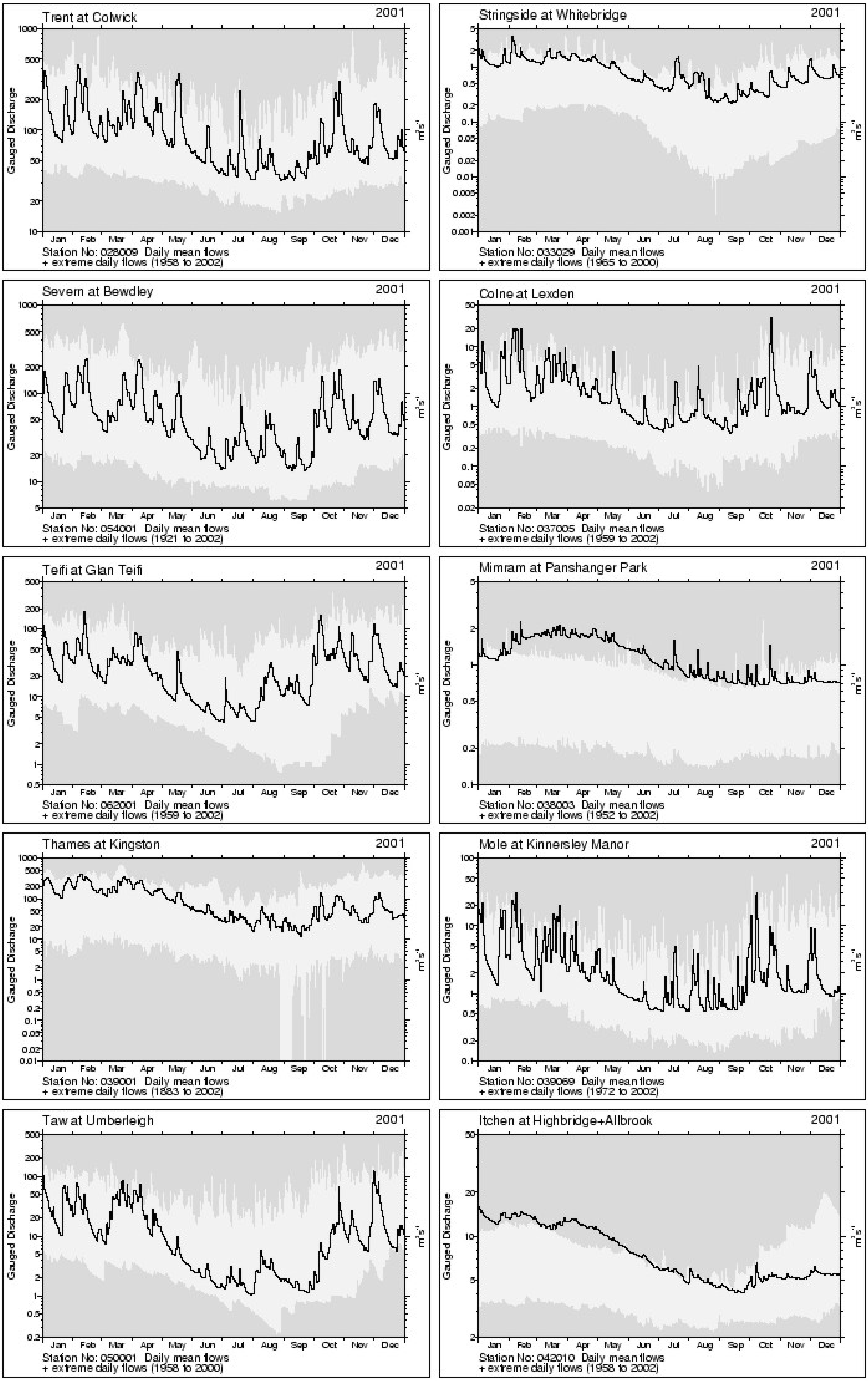


Figure 11 *(Contd.)*

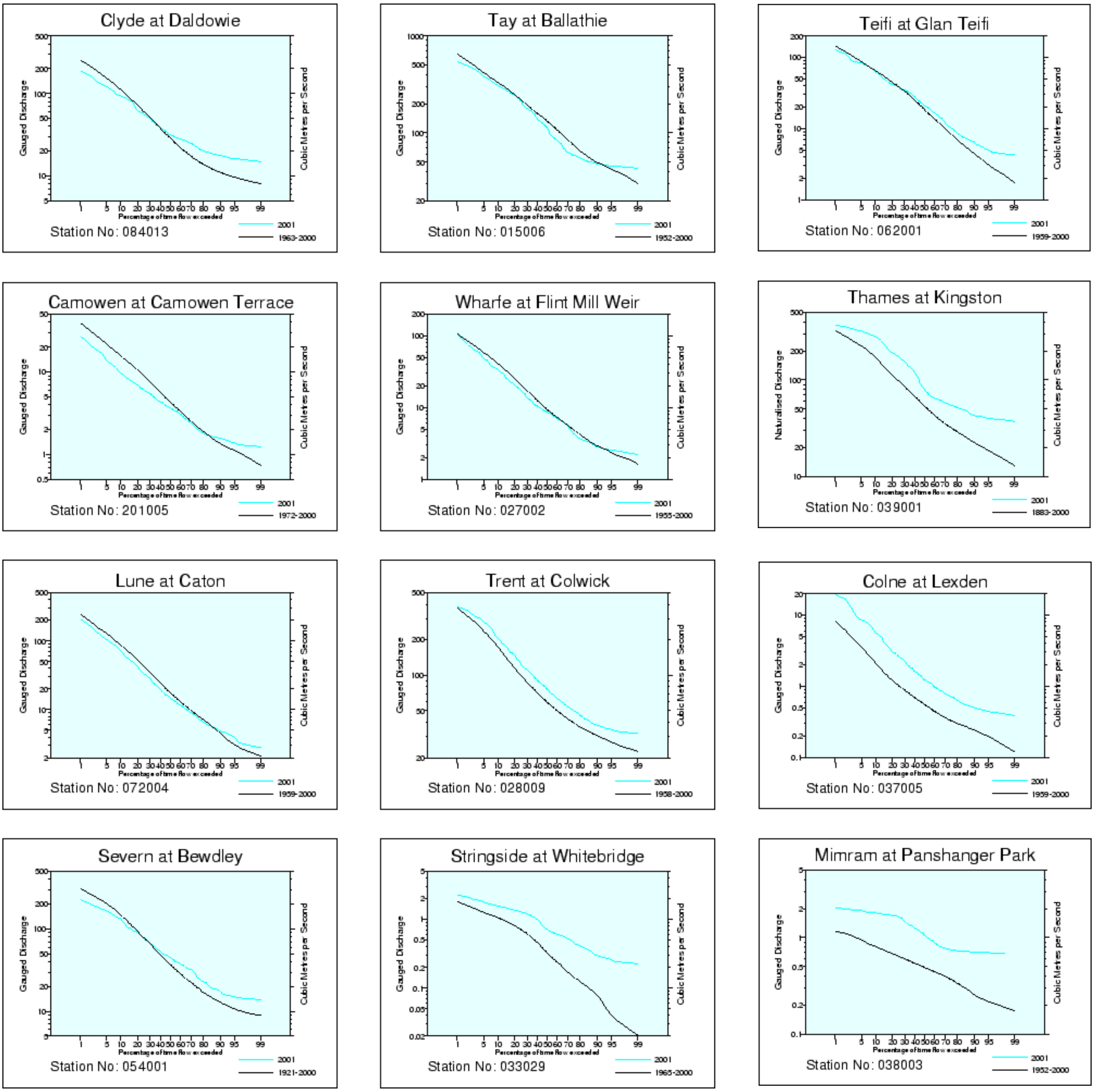


Figure 12 *Flow duration curves for 2001 (in blue) and the preceding record.*

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

October in many western catchments - stalled late in the month; thereafter flows in many rivers dependant on baseflow remained relatively steady until the turn of the year - this implies a considerable decline in runoff rates relative to the monthly average.

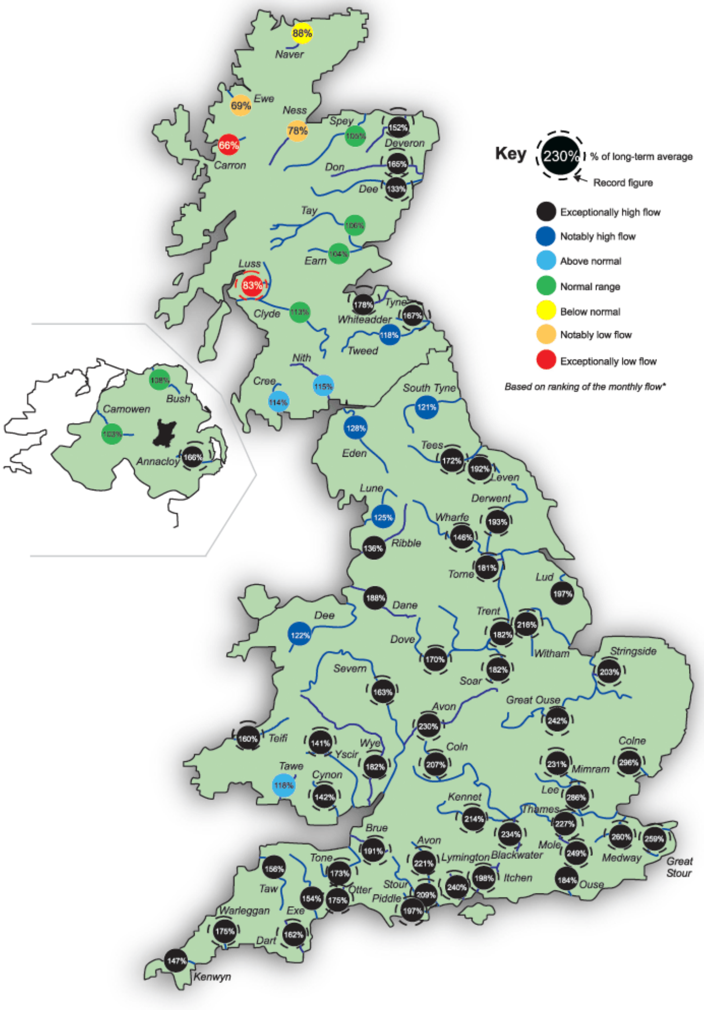
For the second year in succession, river flow patterns across the UK departed substantially from those experienced in a typical year. The unusual nature of the 2001 flow regimes - in southern Britain particularly - is evident from the flow duration curves featured in Figure 12. These curves allow the proportion of time that river flows fall below any given threshold to be identified. Generally, the flow exceeded 95% of the time (a commonly used index of low flows) was greater than the long term average, remarkably so in many spring-fed lowland rivers. In most western and northern rivers the range of flows was appreciably narrower than in a normal year but the most notable duration curves were found in the English Lowlands where, commonly, flows exceeded the long term average throughout the full flow range - confirming the degree to which regimes have been refashioned over the recent past.

River flows - through the year

January began with flood alerts in many catchments across southern Britain and the risk of flooding remained high as outstanding runoff totals were established for the fourth successive month. In contrast protracted recessions characterised many western and northern rivers; from mid-month particularly, low flows were recorded in frozen catchments in northern Scotland. Frozen conditions produced further seasonally depressed flows during February in northern Britain. To the south however, late-winter flows remained close to, or above, bankfull for much of the month; further flooding occurred across the South-East during the second week. Winter (December 2000-February 2001) runoff totals throughout most of the English Lowlands eclipsed previous maxima - often by wide margins; for example the River Itchen established a new maximum 3-month runoff total (for any start-month) - substantially higher than any pre-2001 accumulations.

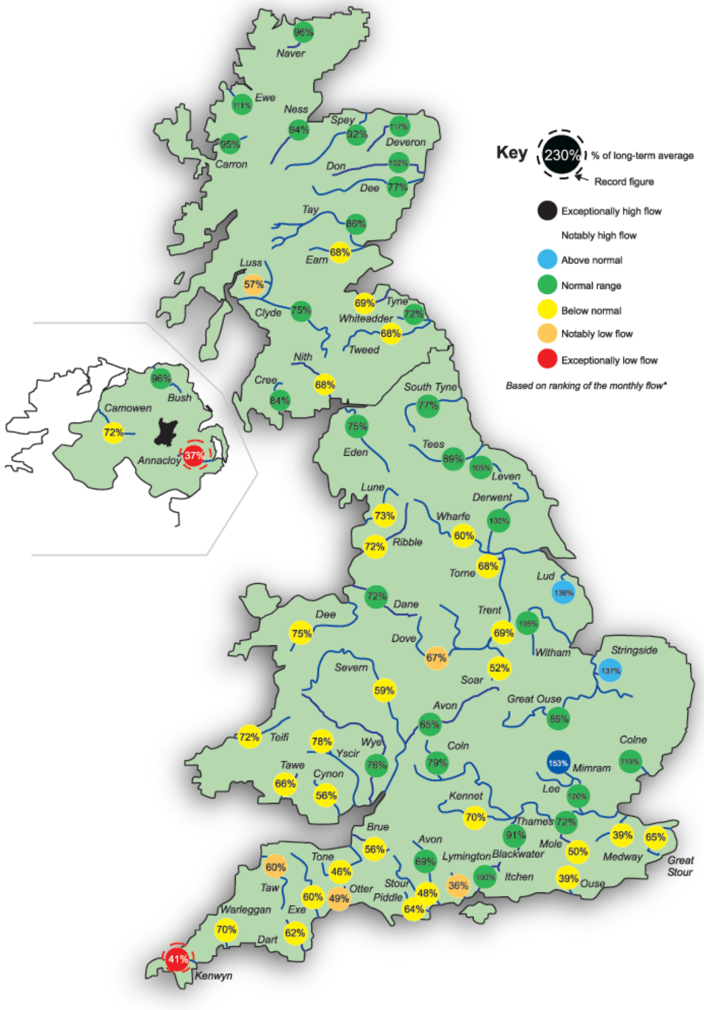
The regional runoff patterns of the late winter continued into the early spring of 2001. Notably low runoff totals were reported from parts of the Scottish Highlands and Northern Ireland - where the River Bush recorded its lowest March flow for 28 years. In contrast, the risk of flooding remained high across southern Britain and monthly runoff totals were again exceptional; many southern rivers established new maximum March runoff totals (including the Lymington and Otter with records of around 40 years). Outflows from many Chalk springs were also without recorded precedent.

Winter half-year (October-March) runoff totals for 2000/01 exceeded previous maxima for the majority of gauging stations in southern Britain. The River Thames established a new October-March maximum in a series from 1883 and previous maxima were commonly exceeded by 50% or more for gauging stations with flow records of less than 40 years. Catchments generally remained close to saturation in April but brisk recessions typified most western and northern rivers. Outstanding flow rates continued in many eastern groundwater- fed streams and rivers, and many further runoff records were established. Some south-eastern rivers (e.g. the Mole and Great Stour) reported October-April runoff (Figure 13) equivalent to around twice the annual average runoff - a remarkable circumstance in a UK context.



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

Figure 13 *October 2000 - April 2001 runoff map.*



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

Figure 14 *November - December 2001 runoff map.*

Dry and warm conditions in May enabled the seasonal river flow recessions to gain momentum but storms in mid-month produced minor floodplain inundations e.g. in the Midlands. Generally, mean flows for May were substantially below those of April across most of the country but some stark regional contrasts were evident by the end of the month - reflecting geological as well as rainfall differences. In most of northern Britain and Northern Ireland flows were relatively depressed at month end; the Tay reported its second lowest May runoff in a 49-year record. However, in southern England the Mimram and Itchen were amongst a substantial number of Chalk rivers establishing new maximum May runoff totals. Many rivers across southern Britain also established new maximum spring (March-May) runoff totals.

River flow recessions continued through June but were commonly interrupted by short-lived spates often associated with thunderstorms - localised urban flooding was common in mid- month in the English Lowlands (e.g. in High Wycombe and Norwich). Healthy flows continued to characterise baseflow dominated southern rivers but late June flows were depressed in some neighbouring impermeable catchments - triggering flow augmentation measures in a few rivers (e.g. the Sussex Ouse). In Scotland and Northern Ireland, mean flows in some rivers were below average for the sixth successive month and a few rivers (including the Luss and Bush) established new minimum January-June runoff totals.

Although the seasonal flow decline was maintained in July, substantial summer spates produced significant local flooding. During the first week exceptional rainfall intensities associated with thunderstorms overwhelmed some urban drainage systems, particularly in Strathclyde and Wales - Llandudno and Bala were badly affected; the peak flow at the New Inn gauging station on the River Dee was the highest in a record from 1971. Local flooding was also common in mid-month in the Midlands and East Anglia - mostly following thunderstorms. Flows in catchments that missed the convective events were substantially below average in most impermeable catchments, e.g. in rivers draining from the Pennines.

This pattern was repeated in August but with a significantly greater frequency of summer spates - generated both by further thunderstorms and sustained frontal rainfall. In Wales, the River Tawe reported its second highest August flow on the 12th and notable spates were common in East Anglia. August runoff totals were mostly well within the normal range but spatial variation was again considerable - flows in the Taw (Devon) were well below average whilst the Mimram - still showing the benefit of the remarkable groundwater replenishment over the winter of 2000/01 - eclipsed the previous August runoff maximum. Summer (June-August) runoff totals were close, or greater than, the previous highest on record for many Chalk rivers.

Thunderstorm-induced runoff events were again common in eastern England during September but in most UK catchments the summer recession stretched into the latter half of the month. Thereafter - and particularly following sustained and widespread frontal rainfall on the 30th - a brisk autumn recovery was initiated in most regions. Although September runoff totals were well below average in most catchments away from the English Lowlands, runoff totals for the water-year (October-September) were the highest on record for most gauging stations in England and Wales - testimony to the extraordinary flows rates maintained throughout the autumn and winter of 2000/01.

Sustained rainfall and the associated decline in soil moisture deficits during October encouraged brisk runoff recoveries across most of the country; these were most noticeable in the north where they were generated from a relatively low base. Spate conditions were common by the second week when the South Tyne recorded its highest October flow since 1967, and more extensive on the 20-22nd when flood warnings were triggered in many catchments. East Anglia was particularly badly affected - the Cam basin especially - and record river levels were reported for several lowland rivers (e.g. the Essex Colne and the Stort and Quin in Herts). At month-end exceptional October flows were recorded in parts of Highland Region and some mudslides (e.g. at Lochcarron) were reported. In a normal year many spring-fed rivers register annual minimum flows during the late autumn but in 2001 autumn flows remained very healthy - more typical of the late winter across southern Britain.

With catchments close to saturation and late October river flows well above average, the risk of flooding was high in early November across large parts of the UK. This vulnerability declined as the month progressed; the very limited rainfall triggering steep recessions in most river basins. With the exception of some rivers draining permeable eastern catchments, November runoff totals were well below average - only around 25% of average for a few southern catchments (e.g. the Kenwyn and Lymington). In Northern Ireland, the Annacloy registered its lowest November runoff since 1983. Autumn (September-November) runoff totals were generally in the normal range but notable longer term runoff deficiencies were developing, in the South-West particularly.

Minor spates occurred across much of the country in early December before the recessions resumed. These were particularly steep in northern Britain where frozen headwaters further restricted tributary inflows. Combined November-December runoff totals were depressed over wide areas (Figure 14) and by year-end flows in some Scottish rivers (e.g. Tay and Luss) approached late-December minima. The continuing absence of any strong seasonal recovery in spring-fed southern streams (e.g. the Lambourn) resulted in the monthly mean flow falling appreciably below average for the first time in around three years.

Groundwater

The year in brief

Rainfall over the outcrop areas of most major aquifers in 2001 was generally close to the 1961-90 average, albeit appreciably above avarage across a substantial proportion of the eastern Chalk. Despite above average evaporative demands, overall infiltration totals were also well within the normal range. However, the overall range in groundwater levels in 2001 was exceptional, a reflection of both antecedent aquifer recharge and the very unusual distribution of recharge through the year - remarkably high totals characterised the January- April period but, thereafter, replenishment was very modest, notably so in relation to the seasonal average during November and December.

In all but the fastest responding aquifer units, groundwater levels reflect recharge patterns over several winters. An important influence on levels in 2001 was the above average rainfall in many aquifer outcrop areas over the winters of 1997/98, 1998/99 and 1999/00 and, particularly, the unprecedented rainfall over the lengthy 2000/01 recharge season. In assessing the impact of this rainfall on groundwater levels it is important to recognise that its relation with aquifer recharge is not a linear one. Evaporation losses have a proportionately much greater impact on recharge in the drier eastern lowlands than in the wetter west. As a consequence, in eastern England, where the Chalk outcrops extensively, a 20% increase in winter rainfall can result in a doubling of aquifer recharge. This non-linearity has been well demonstrated in the recent past.

Entering 2001, groundwater levels throughout most of the UK were close to, or above, previous maxima and - with a proportion of the late-2000 infiltration still to reach the water- tables in many areas - set to rise further through the late winter. The 2000/01 recharge season was exceptionally protracted, exceeding 30 weeks in most regions, and the magnitude of replenishment was without modern parallel (see Table 1). Record groundwater levels continued to be registered well into the spring of 2001 - and later in the slowest responding aquifer units (including large parts of the Permo-Triassic sandstones). Such areas aside, brisk groundwater level recessions became established during the early summer and continued until year end in many eastern outcrops.

Figure 15 shows 1997-2001 groundwater level hydrographs for a selection of index wells and boreholes throughout the UK (see map for the location of the index sites). Five-year plots have been used in recognition that groundwater levels in many areas show considerable persistence. The 5-year format also allows the outstanding range in groundwater levels over the recent past to be illustrated. The groundwater level trace is shown together with the monthly maximum and minimum levels for the pre-1997 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 in late 2000. In overall resource terms, an important contrast can be drawn between most of the last four years - when groundwater levels have been generally above average, and the depressed levels of the 1995-1997 period; in the summer of 1997 groundwater levels were historically depressed across much of the UK.

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 groundwater 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 (Figure 16) but the rise since 1999 has been much more modest with relatively stability characterising level variations through 2001. 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.

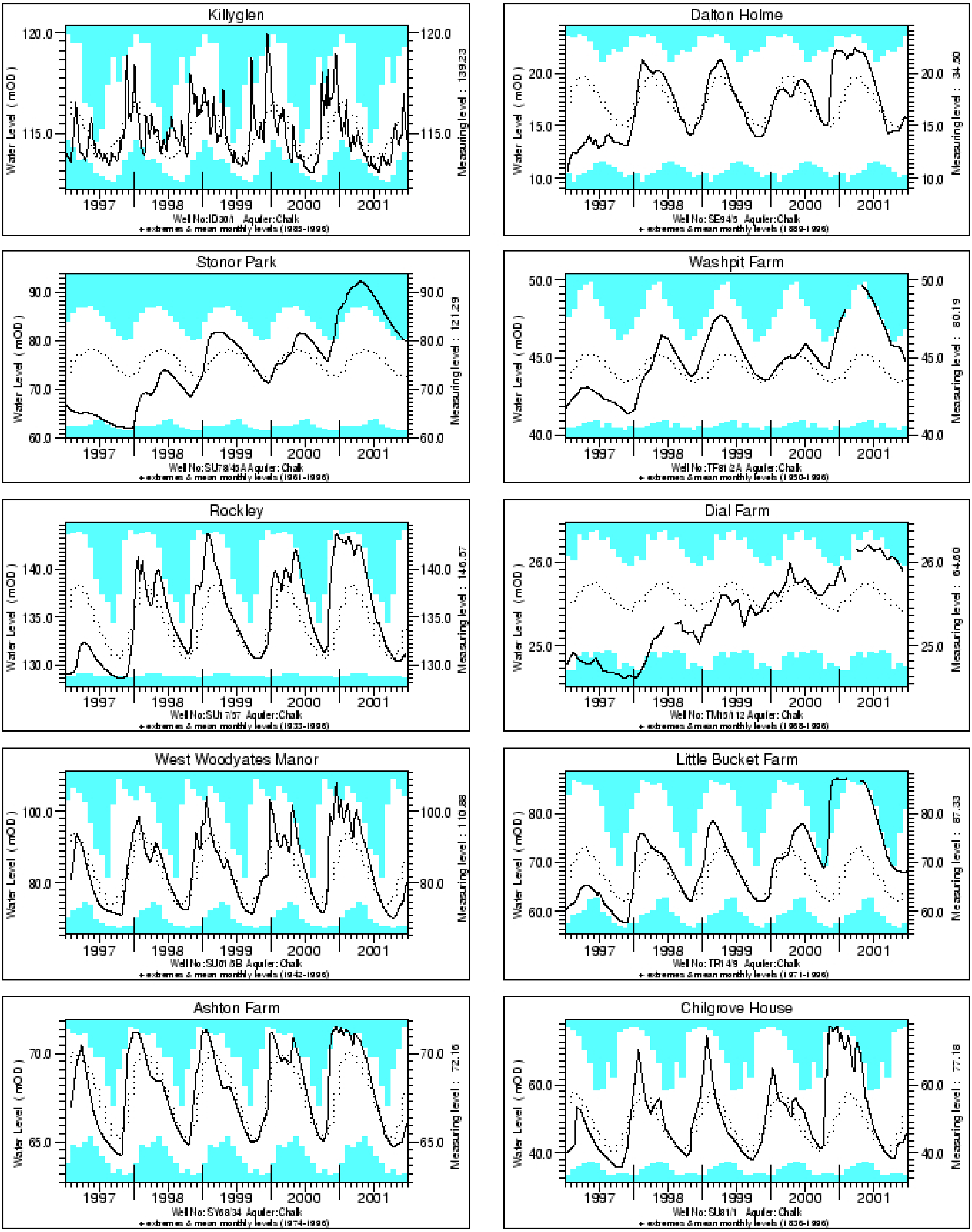


Figure 15 *Groundwater level hydrographs 1997-2001.*

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

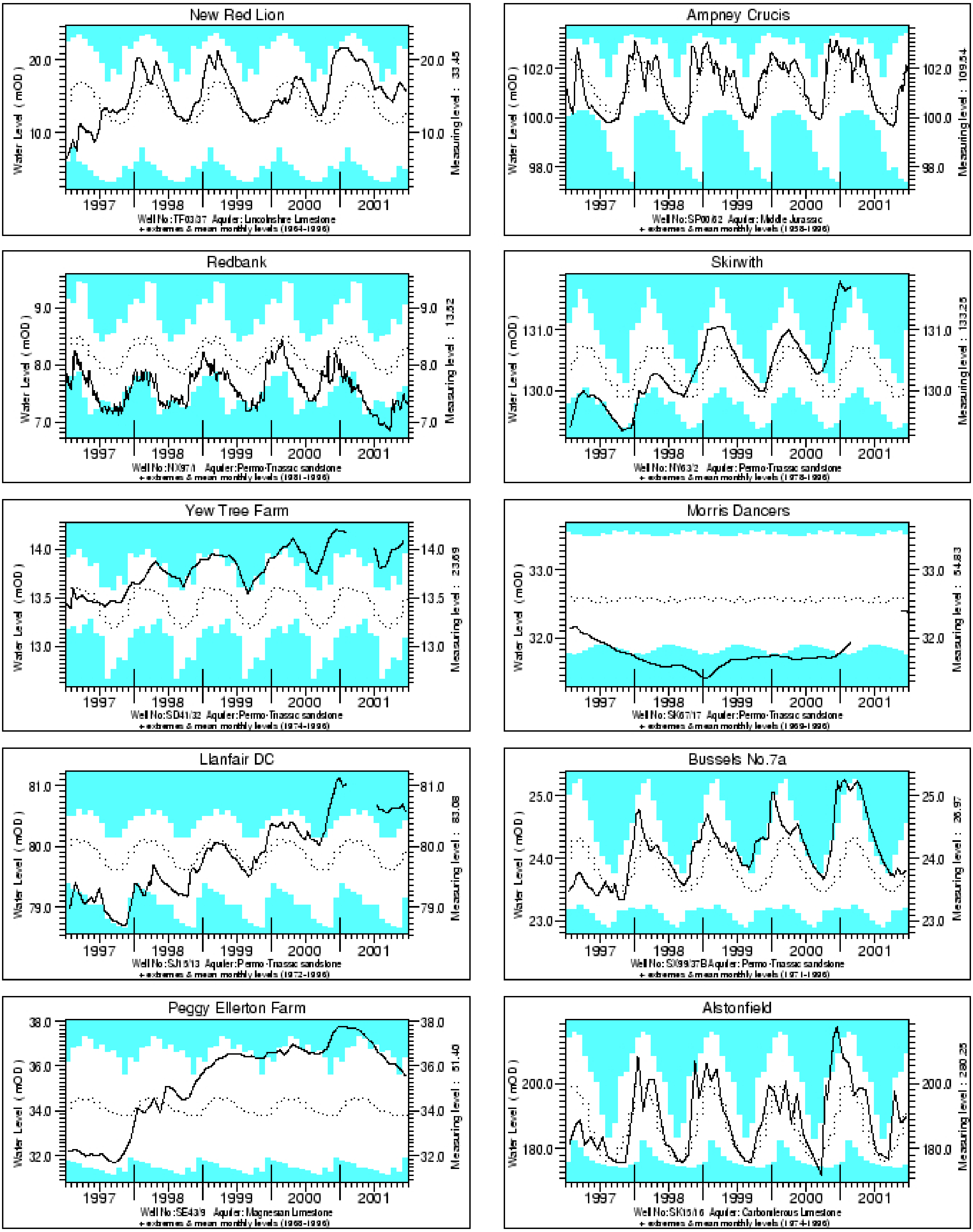


Figure 15 *(Contd.)*

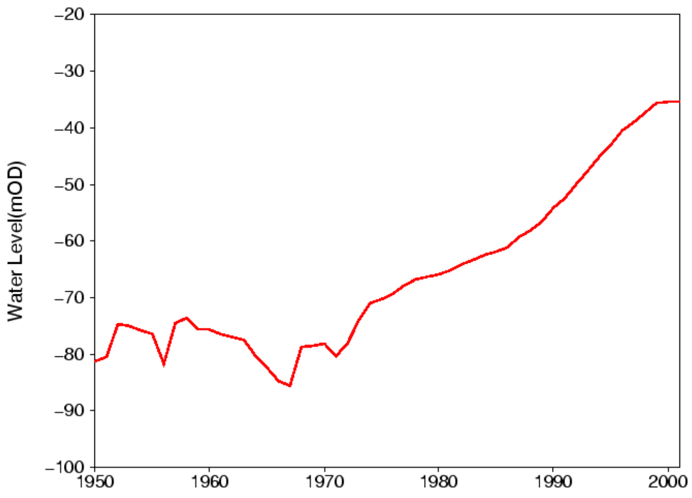


Figure 16 *Groundwater levels at Trafalgar Square 1950-2001.*

Groundwater levels - through the year

Following record recharge rates during the last three months of 2000, abundant infiltration continued through January as all aquifer outcrop areas remained saturated. Some brisk declines from the remarkable groundwater levels in December were recorded (e.g. in the Carboniferous Limestone of Derbyshire) but, generally, levels continued to rise. Overflowing wells and boreholes were commonplace in many parts of the Chalk outcrop, in southern England especially. Water-tables reached the surface in many 'dry' chalk valleys producing surface flows at previously unrecorded levels and persistent 'clearwater' flooding was experienced in many areas.

Rainfall in February was around twice the average in parts of East Anglia and the associated heavy recharge produced further rises in groundwater levels throughout much of the eastern Chalk. In Kent, the Little Bucket borehole overflowed - thought to be for the first time (in a 40-year series) and many observation wells reported new maximum levels (for any month). Initial analyses indicate that overall resources in the Chalk (the most important aquifer in water supply terms) were greater than at any time for which directly recorded level data are available. Unprecedented groundwater levels were also reported for the Permo-Triassic sandstones and Magnesian Limestones - and for most minor aquifers in eastern England (e.g. the Norfolk Crag and Essex Gravels). Following winter recharge totals that were three or four times the long term average in much of southern and eastern England outflows from springs were of an unprecedented magnitude - and, in many areas, still increasing.

Access restrictions due to the outbreak of Foot and Mouth disease severely disrupted the collection of groundwater level data in March when infiltration rates were again very heavy. Rapid drainage from high level springs and seepages reduced groundwater levels in some more responsive aquifer units, but generally levels remained historically high - well above pre-2000 maxima across much of the Chalk. Levels in the deep and slow-responding Therfield Well (near Royston), reached their highest since the First World War. Locally (e.g. in the upper Pang catchment, Oxfordshire) pumping was undertaken to help reduce groundwater levels in areas subject to significant flooding. Despite such measures, 'clearwater' flooding remained common and persistent - prolonged basement flooding and transport disruption was widespread in southern and eastern England.

By April, during which recharge rates were again exceptional, previous groundwater level maxima were exceeded across many outcrop areas (Figure 17). Pre-2000 maxima were eclipsed by margins which approached the average annual range across parts of the Permo- Triassic sandstones outcrop (e.g. in the Midlands). At Weeford Flats, where the borehole was dry in early 1999, levels rose briskly through April and were approaching the long term maximum in a series from 1966. In the Chalk, groundwater levels at Stonor, in the Chilterns, peaked around four metres above the pre-2000 maximum and extremely high spring outflows were maintained in many areas.

Below average rainfall in late April and May, together with accelerating evaporative demands and a corresponding rapid increase in soil moisture deficits signalled the end of the most remarkable recharge episode on record for the UK. This heralded a decline in groundwater levels - but its pace was very dependant on aquifer characteristics. In the slow responding Permo-Triassic sandstones and in parts of the eastern Chalk, levels remained above pre-2000 maxima for many further months and clearwater flooding was experienced well into the summer.

June was also dry and notably high soil moisture deficits characterised most areas at month-end. Correspondingly, infiltration was restricted to very localised storm events. Steep groundwater level declines were reported for responsive aquifer units (e.g. the Carboniferous Limestone of Derbyshire) but the large volume of water percolating through the unsaturated zones above many water-tables continued to generate groundwater level increases, in the Permo-Triassic sandstones especially. Overall groundwater resources for England and Wales during the early summer of 2001 were healthier than is normally encountered in the late winter.

The easing of Foot and Mouth restrictions in July helped confirm the contrasting responses in different aquifer types to the dry late spring and early summer. Levels in the western and northern Chalk (generally more fissured and more responsive than in the eastern Chalk)

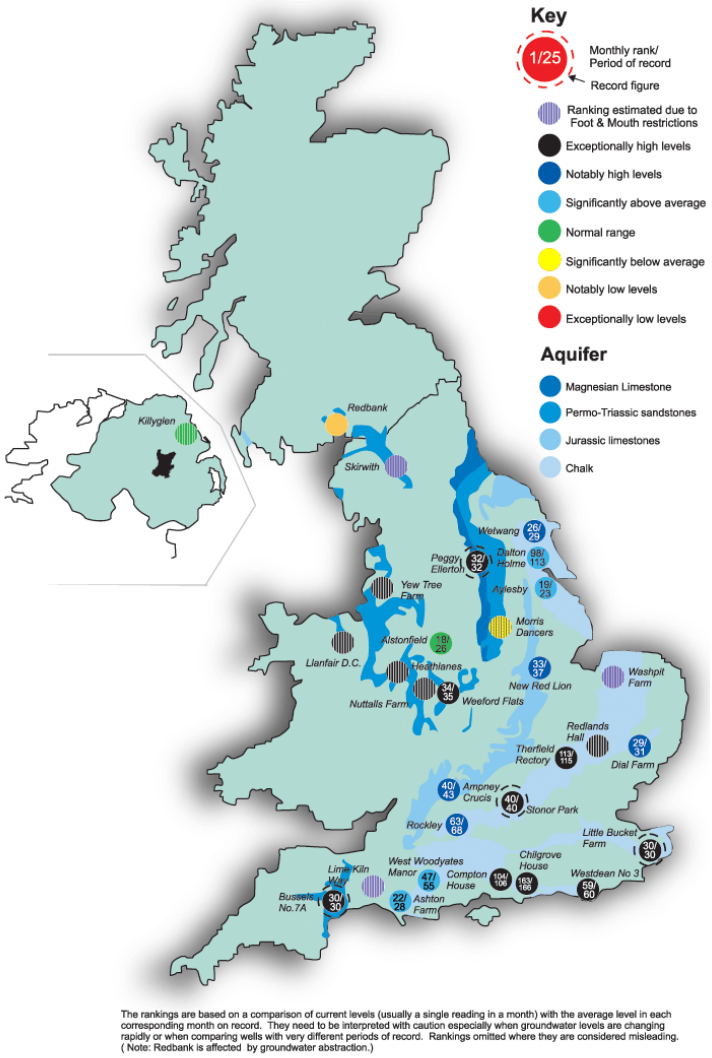


Figure 17 *April 2001 groundwater levels.*

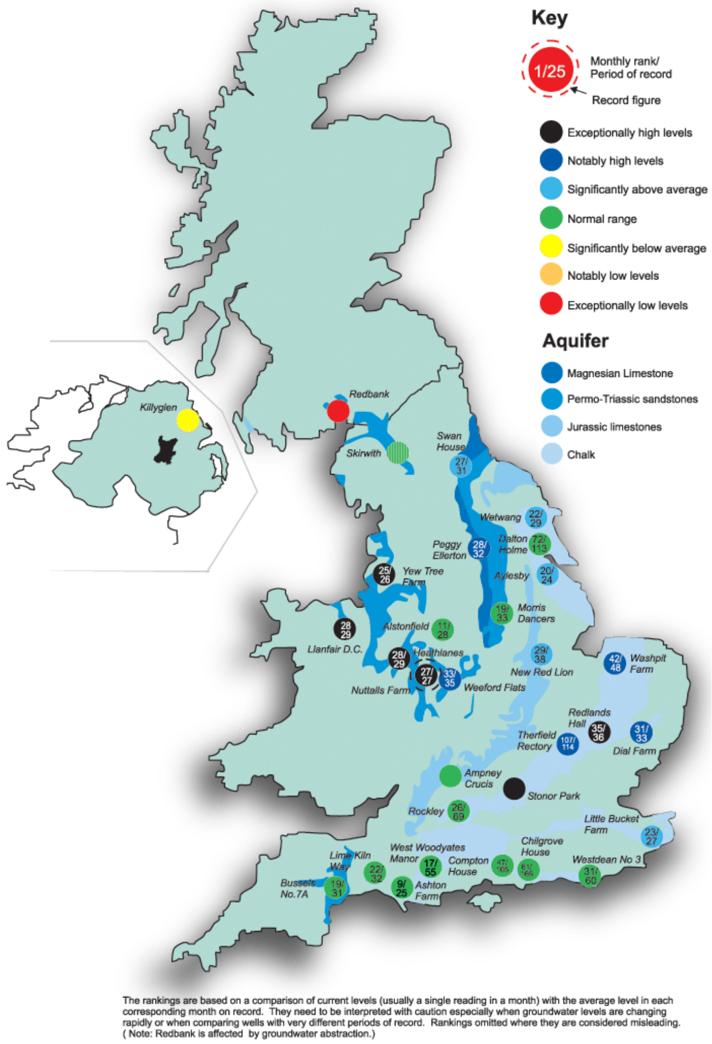


Figure 18 *December 2001 groundwater levels.*

had returned to within the normal summer range; this was true of much of the Carboniferous and Jurassic Limestone outcrops also. However, throughout much of the Permo-Triassic sandstones aquifer new period of record maxima were being established (e.g. at Heathlanes) whilst previous monthly maxima were still being eclipsed in the Chalk during August (e.g. at Stonor and Yew Tree Farm).

By September however recessions were well established in almost all aquifer units and by month-end levels in most limestone and some Chalk observation wells and boreholes had fallen to within the normal seasonal range. Sustained rainfall in October - which favoured the outcrop areas of the major aquifers - produced a steep decline in soil moisture deficits and initiated the seasonal recovery in groundwater levels across much of the country late in the month. In a few Chalk outcrops (e.g. in Dorset), the recovery began from a low base but in the eastern Chalk and across many Permo-Triassic sandstones outcrops it began with groundwater levels close to the October maxima. This gave rise to concern that even with 2001/02 recharge totals within the normal range there was a significant risk of further groundwater flooding through the winter of 2001/02.

Parts of eastern England excepted, soils remained close to saturation through November but - fortunately from the flood risk perspective - rainfall totals were well below average and, as a consequence, the groundwater level recoveries gained little momentum. In most outcrop areas December was even drier resulting in a stalling of the groundwater level recovery in all regions. In parts of the Chalk levels remained close to those of the preceding summer. The year ended with a very spatially diverse pattern of groundwater storage (Figure 18). Below average levels characterised parts of the western Chalk whilst throughout parts of the Permo- Triassic sandstones outcrop levels remained above pre-2001 maxima.

Reference

1. Manley, G. (1974) Central England Temperatures: monthly means 1659 to 1973. Quart. Jour. Royal Met. Soc., 100, 389-405.

Location Map

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