Report

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A review of the GLA drought severity assessments presented at the Beckton Gateway WTW Public Enquiry

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Introduction

This short report, commissioned by Thames Water Utilities, examines recent drought episodes in the Thames catchment. It gives an assessment of their severity and places them within the context of other major droughts over the last 200 years. Such an extended historical perspective is particularly helpful when assessing the credibility of contemporary droughts which are designated as extreme. Different approaches to indexing drought severity are considered with a particular focus on whether return periods associated with rainfall deficiencies alone represent a reasonable basis for assessing the relative severity of droughts in relation to water resources stress.

The report focuses on runoff deficiencies most critical for London's water supply. It includes droughts before 1920, although these cannot be fully modelled from a water resource analysis perspective as full data coverage is not available.

The Thames basin – hydrometeorological background

Average annual rainfall over the Thames basin is around 700 mm distributed fairly evenly through the year but with a moderate tendency towards an autumn maximum. On average 65-70% of the rainfall is lost to evaporation, concentrated mainly in the summer. This imposes a marked seasonality on the Thames flow regime and aquifer recharge patterns. During the summer, when dry soil conditions greatly restrict surface runoff, most of the river flow derives from extensive aquifer outcrops within the Thames basin; on average natural groundwater outflows constitute about half of the Thames flow at Kingston. This substantial baseflow is especially important during drought episodes.

Drought is a recurring feature of the UK climate and the Thames basin is inherently susceptible due to the relatively modest margin between average rainfall and actual evaporation losses. A relatively modest decrease in rainfall – during the winter especially – can produce disproportionately large reductions in runoff and aquifer recharge. In water resources terms, deficiencies in runoff and recharge rates are the principal cause of drought stress although high temperatures can be an influential factor (e.g. by increasing water demand or exacerbating water quality problems).

Indexing drought severity

Droughts are multi-faceted both in their character and range of impacts. Developing objective procedures for indexing drought severity is a considerable scientific challenge (Tallaksen and van Lanen, 2005; Mawdsley et al, 1994). In part this reflects the difficulty of quantifying a phenomenon which varies in its extent, duration and intensity both regionally and locally. In addition, distinctions can be drawn between meteorological droughts, defined primarily on the basis of rainfall deficiency, agricultural drought, where the focus is on soil water content through the growing season, and hydrological drought, which results from substantial deficiencies in runoff and/or recharge. The latter category is of most relevance to water resources management.

Assessments of rainfall deficiency are a common starting point in drought analyses and are of particular importance in relation to Drought Order applications. Ranking of n-month rainfall totals or the calculation of associated return periods provides an index of the relative severity of various droughts episodes. However, such assessments typically focus on the longest duration or most intense phase within an individual drought episode. This is understandable but the timebase chosen may bear little relation to the critical period of any given water resources system. Even exceptionally rare summer rainfall totals may have only a limited impact on water supplies from large reservoir systems or aquifer units (replenishment being primarily dependant on the winter and early spring rainfall). For these reasons it is important that an overall view of the robustness of the water supply system to droughts is assessed. Typically this is undertaken through water resource simulation modelling.

Comments on the return period evidence presented on behalf of the GLA

The GLA evidence lists seven droughts over the last 30 years. The return periods (RPs) quoted are not based on any recent analyses but derive from contemporary published assessments of drought severity based on rainfall deficiencies. The rarity associated with the 2003 drought may be an exception; on the basis of rainfall alone (Tabony Tables), the Feb-Oct drought would be expected to have a return period in the 60-90 year range.

Whilst rainfall figures can provide a very helpful index of, say, agricultural drought stress during the spring and summer, they have less utility in relation to water resource applications. This is especially true of the English Lowlands where the majority of rainfall is lost to evaporation. One consequence is that drought severity estimates based on rainfall alone can be very misleading. As an illustration, consider the 1995 drought – an exceptionally arid 5-month episode (the April-August rainfall total is the lowest on record for the Thames basin). A return period of 80-120 years is given in the GLA evidence. Over this period, accumulated runoff (naturalised) for the Thames at Kingston was well within the normal range - with a recurrence interval of around three years only. Groundwater levels also remained well within the normal range, a consequence of heavy recharge through the winter of 1994/95. For the Thames region, the 1995 drought was not an outstanding event in runoff terms when

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considered in the context of droughts over the preceding 50 years, let alone over a longer 150 year time series (see below).

Rainfall and Tabony Tables

Assuming that the rarities quoted for the featured droughts are exclusively rainfall-based, several points need to be made regarding the credibility of the return periods quoted:

i. The RPs appear to be based on Tabony Tables (a standard approach – Tabony, 1977) which reflect, or are constrained by, rainfall variability over the 1911-1970 period. With regard to drought conditions, the 1911-1970 time-span is now known to be a relatively quiescent period. Use of a longer base period, embracing the droughts in the 1890-1910 and post-1997 periods may be expected to reduce RPs very substantially (see below).

ii. The RPs derive from 'fixed start month' analyses. It is important to recognise that analyses based on 'any start month' would give much lower return periods; around an order of magnitude for 12 month durations. As an illustration, the quoted >200 years RP for the 1990 drought relates to the March-November period specifically. If 9-month deficiencies beginning in any month are considered, the Mar-Nov rainfall in 1990 ranks 4th lowest in a series from 1883; the 1976 drought was considerably more intense.

iii. The Tabony Tables approach makes no allowance for climate change.

iv. As indicated above, the RPs generally relate to the period with the most severe rainfall deficiency within each drought episode. The episodes featured range from 5-24 months in duration. Clearly, most will not closely coincide with the critical period for water resource management in the Thames catchment.

Such limitations help explain the statistical paradox of the Thames basin apparently experiencing three extreme droughts (RP >= 100 yrs) within 6 years (1990-95). More comprehensive examination of the droughts' features (e.g. Hamlin & Wright, 1978, Marsh et al, 1994) demonstrate that, with a couple of exceptions, severities based on river flows (or groundwater levels) differ markedly from those based on fixed-period Tabony Table appraisals and as such are a much more representative assessment of the severity of the drought and the potential impact on the water supply system.

The GLA evidence states that 'all return period estimates taken from Institute of Hydrology/National Water Archive publications', but the specific references are not given. More importantly, no discussion is included of the uncertainties associated with the rainfall return period estimates (see below) or, crucially, of the drought severity assessments featured in the various references based on runoff deficiencies or groundwater resource status. The differences with the rainfall-based assessments are, in most cases, revealing and important. For example, the return periods for a wide

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range of n-day (naturalised) minima for the Thames during the 1984 drought is given as 2 years (Marsh and Lees, 1985); the rainfall-based severity is 10-20 years. Similarly, the >200 year RP for rainfall during the drought of 1990 compares with a runoff ranking of 19/110 for the Thames over the April-August period (giving an indicative RP of about 6 years). Both the rainfall and runoff severity assessments have validity in an appropriate context but, clearly, the use of rainfall-based severity estimates in circumstances where the focus is on the water resources (rather than the meteorological) dimension of drought has real potential to mislead.

Accumulated runoff and groundwater levels as indices of drought severity

Catchment runoff and aquifer recharge provides an integrated measure of the complex interactions of the various climatological causes of drought. Correspondingly, runoff or recharge deficiencies – over an appropriate timespan – provide a better index of drought severity than rainfall deficiencies, especially for water resources applications. From a water supply perspective river flows are important in London as a large proportion of supply ultimately comes from river abstractions. These in turn have particular licence constraints which need to be met. For water supply in London, the severity of 2-season runoff deficiencies are considered particularly critical.

The River Thames flow record

The daily flow record for the Thames extends back to 1883. Prior to the major refurbishment at Teddington in 1951, the gauging facilities had been improved or extended on a number of occasions. However, leakage through the weir led to underestimation of pre 1951 low flows (Littlewood & Marsh, 1996).

Over the last 120 years abstractions from the lower Thames have increased by more than an order of magnitude and now, on average, constitute around 40% of the natural flow. Largely as a consequence, minimum accumulated gauged runoff totals (see Table 1) are disproportionately concentrated in the last 20 years. When naturalised minima are examined a more realistic picture of relative drought severity emerges, although the underestimation of low flows prior to 1951 will certainly influence the ranking positions of the droughts featured. Systematic errors in the estimation of 'variations' (non-returning abstraction upstream of Teddington) could also be a factor.

Table 1 Minimum non-overlapping 6-month runoff deficiencies for the Thames at Teddington/Kingston for 1883-2006.

Rank	*Gauged runoff (mm)*	*End month*	*Naturalised runoff (mm)*	*End month*

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1	6.0	Sep 1976	23.2	Nov 1921
2	7.6	Nov 1934	24.1	Nov 1934
3	8.3	Nov 1990	27.0	Sep 1944
4	9.4	Nov 1921	28.8	Sep 1976
5	11.6	Oct 1944	31.2	Oct 1899
6	12.0	Sep 1997	31.4	Nov 1901
7	13.2	Nov 2005	34.5	Nov 1893
8	13.3	Dec 1996	34.9	Nov 1900
9	14.0	Nov 1989	35.3	Oct 1929
10	17.4	Nov 1943	35.3	Nov 1943

N-day minimum flows

Frequency analyses of annual minimum n-days flows are commonly used to compare drought severities and assign return periods to individual drought events.

Return periods associated with frequency analyses can be very sensitive to the impact of particularly severe drought episodes. For instance, sustained drought conditions over the 1989-92 period resulted in a large reduction in the return periods associated with annual n-day minima on the Thames (Marsh et al, 1994). Over time therefore contemporary assessments of drought severity may lose both credibility and relevance. An assessment of the relative severity of a drought will thus change over time. However, it is important to note that this needs to be decoupled from the impact that such a drought would incur from a water supply perspective as this will remain unchanged (in absolute terms the flows are what they are in that year).

Table 2 lists the 10 most notable 30- and 120-day minima for the Thames naturalised flow series since 1951; Fig.1 is the corresponding Flow Frequency Diagram. This shows that the recent low flow episodes are relatively moderate in their severity compared to the last serious drought in 1975/76 and in part explains why from a water supply perspective London has not experienced any severe demand restrictions.

Table 2 10 most notable 30-day and 120-day minima for Thames at Kingston since 1951

Year	*30-day minima (m^3/s)*	*Year*	*120 day minima (m^3/s)*
1976	10.8	1976	14.2
1990	18.2	1990	20.8
1997	18.9	1996	22.1
1996	19.0	2005	23.5
1959	19.7	1997	24.2
1991	20.3	1989	24.3
2005	20.5	1953	25.9
1989	21.4	1991	26.6
1995	21.7	1959	26.8
1953	22.6	2003	27.3

Severity and duration of major droughts in the Thames basin – an overview

[1]

In a global context, the Thames basin is well blessed with lengthy records of hydrometeorological data upon which to base assessments of drought severity. Rainfall data extend back to the 17th century and a few spring flow, river flow and groundwater level series extend back into the nineteenth century.

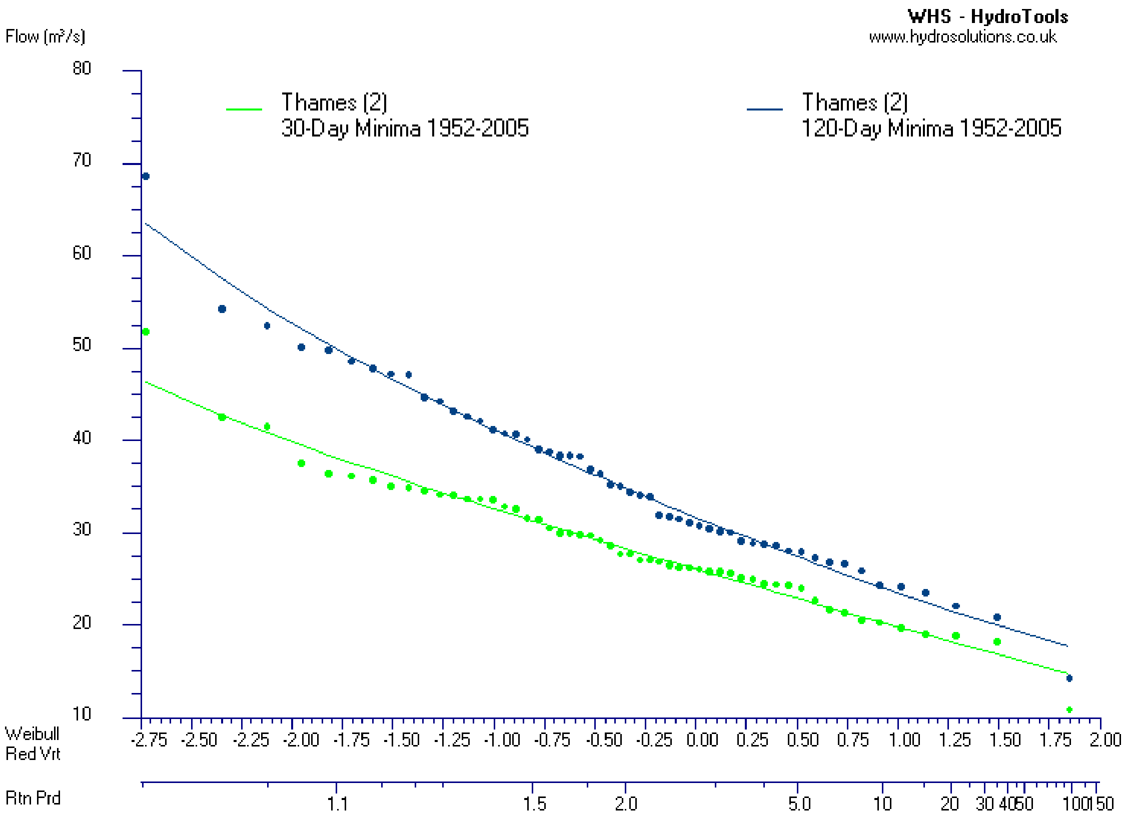

Fig. 1 Flow frequency diagram for Thames at Kingston (naturalised flows) 1952-2005

Appendix A features monthly catchment rainfall and river flow time series for the Thames catchment above Teddington/Kingston and the River Lea above Feildes Weir. Also shown is a long term hydrograph for the Therfield Rectory well in the Chalk to the north of London[1]. Periods of deficiency are shaded red and a logarithmic scale is used to further emphasise the drought episodes. The blue and pink envelopes indicate the long term maxima and minima on each plot.

The plots are not intended to provide an absolute means of comparing drought severity but visual appraisals do allow a flexible synthesis of the various hydrometeorological components of drought which is often lost in more mechanistic statistical analyses. The extended dry periods in 1921/22, 1933/34, 1943/44 and

[1] Appreciable hydrometric uncertainty exists regarding the early groundwater level record for Therfield Rectory. Nonetheless, the periods of sustained depressed levels, and particularly the periods when the well was known to be dry, are important indicators of groundwater drought severity.

1975/76 are clearly evident. The prolonged nature of the 1988-92 drought is also evident, as is its particular severity in groundwater terms and the temporal variation in its severity. The plots provide a visual confirmation that the post-1990 drought episodes are not unprecedented. Importantly also, there is no modern parallel to the very extended drought conditions experienced prior to 1910. Several important examples of very extended drought conditions prior to the well documented 1921/22 event, include the very sustained rainfall deficiencies from 1798-1808,1854-60 and 1890-1905.

The 'Long Drought' 1890-1905

Drought conditions for the 15-year period beginning in 1890 merit particular attention – not least because this important drought episode is not well documented but also because there is insufficient data to model this from a water supply perspective. It was characterised by sustained low winter rainfall – six dry winters in succession – but includes several very wet interludes. Drought conditions were intense during hot dry summers (1893 in particular), but the remarkable persistence was largely due to a paucity of aquifer recharge and the corresponding depressed groundwater levels, and associated long term failure of springs (Bayliss et al, 2004).

A repetition of the 1890-1905 seasonal rainfall distribution, when cumulative effective rainfall totals were particularly depressed, would represent a substantial water resources challenge in the Thames basin given current water demand patterns.

Major droughts featured in the GLA evidence

The data presented above shows runoff based assessment are a more suitable metric by which to assess drought severity than rainfall deficiency data alone. Examination of previous droughts (Thames ref??) suggests that the water supply system of the lower Thames appears to be most severely affected by six to nine month droughts, generally ending in late autumn/early winter. Thus consideration of critical droughts should focus primarily upon this type of event.

Table 3 compares the return periods featured in the GLA evidence with three runoff-based assessments. The first gives indicative estimates based primarily on runoff deficiencies, but informed by rainfall patterns and contemporary groundwater level data from two index wells in the Chalk (Therfield and Rockley). The second and third derive from the n-day minima analysis featured above using data from 1952 and relate to different, but complementary, aspects of river flow deficiency – 30 and 120 days. In both cases, the rarity of the droughts post-1990 under review is markedly lower than the return periods quoted by the GLA. The effect of antecedent conditions is a factor here, and some relevant influences are summarised in the comment column. The data also highlight the importance of long run water resource simulation to assess the robustness of the supply system to the temporal variation in the drought severity. For example, the 1990-1992 drought shows considerable temporal variation in its severity.

Table 3 Comparison of return period estimates for selected Thames droughts

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Drought	Start	End	GLA return period (yrs) (rainfall)	Indicative [3] return period	30 -day min RP	120- day min RP	Comment
1976	May 1975	August 1976	1000	30-60	>100 [2]	>100 [2]	Extremely severe in rainfall, runoff and groundwater terms, but bracketed by wet conditions which aided water supply & some residual benefit from heavy groundwater replenishment in winter 1974/75 .
1984	April 1984	August 1984	10-20	<2	5	3	Very minor drought in runoff & groundwater terms, bracketed by wet conditions.
1990	March 1990	Nov. 1990	>200	5-10	35	35	Very wet preceding winter so flows well sustained until late 1990. Steep recession followed, which heralded long drought (1990-2).
1990-92	March 1990	Feb. 1992	>200	30-40	1991 10 1992 2	1991 7 1992 2	A notably long drought in terms of rainfall & river flows which had a strong groundwater dimension and a temporal variation in intensity.,
1995	April 1995	August 1995	80-120	<3	6	5	Very severe spring/summer rainfall deficiencies, but bracketed by wet periods. Winter recharge provided flow support through much of 1995. However low autumn flows in 1995 foreshadowed another sustained drought through 1996 and 1997 (when both groundwater and reservoir stocks were depressed) – not mentioned in GLA evidence.
2003	Feb. 2003	Oct. 2003	20 (60-90) [1]	<3	5	6	Exceptionally high flows and groundwater levels in January 2003. Steep recession but accumulated runoff well within normal range.
2005/6	Nov. 2004	ongoing	30-40	15-20 drought still developing	8	15	Notably severe 2-winter drought in rainfall, runoff and groundwater terms. Unlikely to see recoveries before late autumn. Another dry winter could establish outstandingly severe drought conditions.

[1] from Tabony Tables

[2] A 50-year record is insufficient to determine this RP of such an extreme event with any confidence

[3] Indicative return periods based on judgement informed by n-month runoff and rainfall deficiencies and groundwater data

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It is suggested that, taken together, the GLA return periods constitute an unrealistic assessment of drought risk implying a clustering of extreme events which is unsupported by other, more relevant, hydrometeorological evidence.

A note on the current drought

The current drought began in the autumn of 2004 and intensified through the exceptionally dry and mild winter of 2004/05. With most rain-bearing frontal systems following tracks remote from the English Lowlands, the drought's focus in 2005 was in the South East. This remained generally true through a second dry (but cold) winter (April 2006 being the 16^{th} month in the last 18 with below average rainfall for the Thames catchment), and very low summer river flows and groundwater levels are in prospect. However, as with all droughts one cannot predict when it will end nor whether it will intensify or weaken. That is the nature of droughts.

Conclusion

This assessment has underlined some of the complexities associated with assigning severity assessments to drought events of varying provenance, duration and intensity. Some clear signals have emerged and are important when assessing the robustness of the water supply system to droughts:

- On their own, rainfall-based return periods can provide a very misleading indication of drought severity.

- Notable drought events are a recurring feature in the Thames basin. There are four key low flow periods since 1920 with further extended dry periods during the preceding 120 years.

- Runoff-based assessments of drought severity (6-9 months) confirm the severe nature of the 1975/76 drought as well as the notable severity of 1921/22, 1933/34 and 1945/46 droughts.

- There are more than 10 events of comparable or greater severity in terms of runoff deficiency than the post-1990 events referred to in the GLA evidence.

- The GLA evidence substantially overstates the severity of the drought events in the 1990s.

- The cluster of droughts in the recent past is notable but not outstanding in the context of the last 200 years

- Pre-1921 drought events merit more attention when considering information bases upon which to explore runoff and recharge scenarios not well represented in the recent past, however, a lack of full spatial data coverage makes an objective assessment of these droughts on water supply capability difficult

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- A full assessment of drought severity with regard to water supply capacbility needs to take into account the overall response of the catchment, the demand placed upon it and the licensing arrangements. Due to the temporal and spatial variations within any individual drought event, such analysis should look over as long a period as record as possible.

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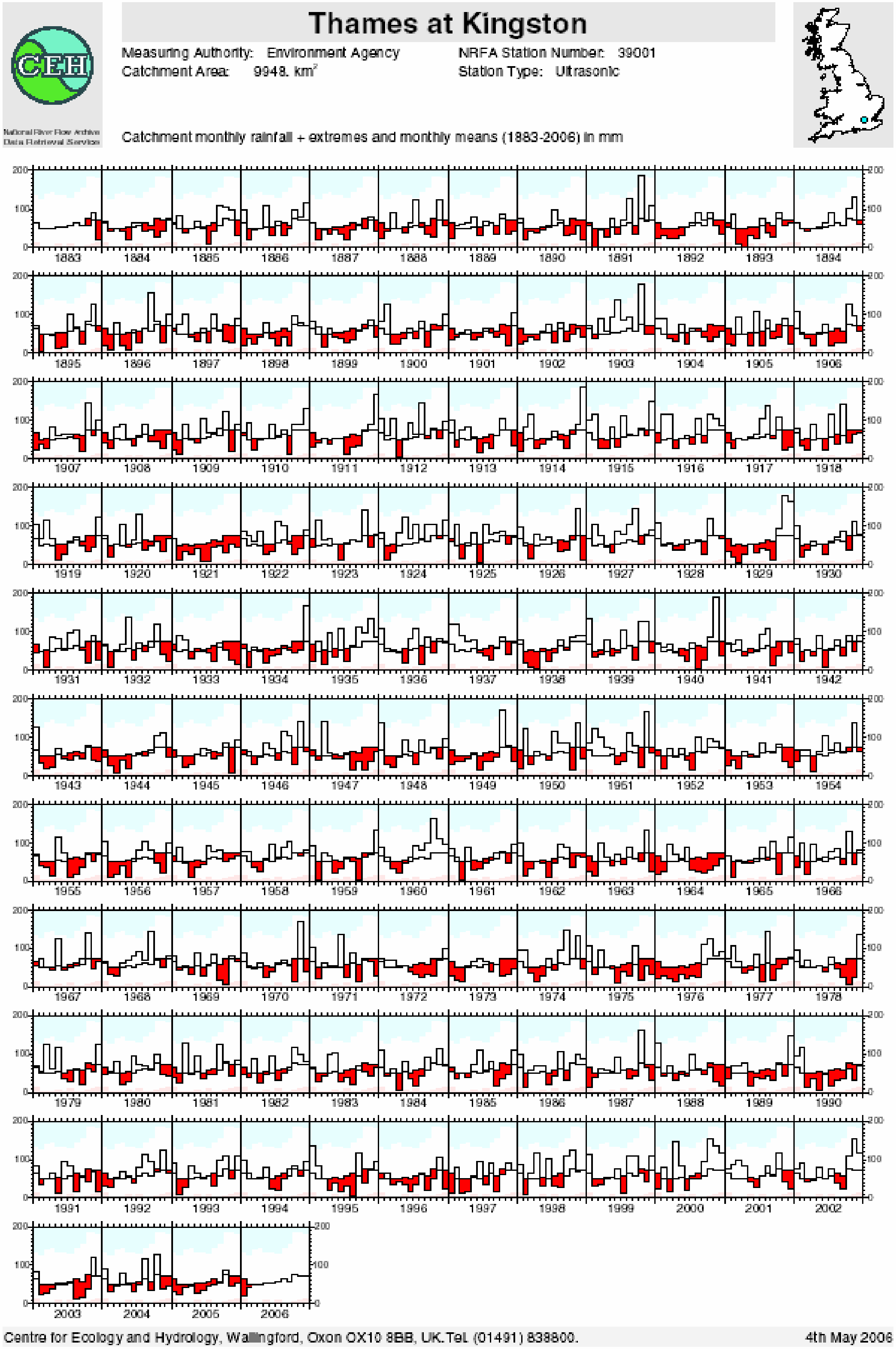
APPENDIX A
A1: Time series of monthly catchment rainfall -Thames at Kingston



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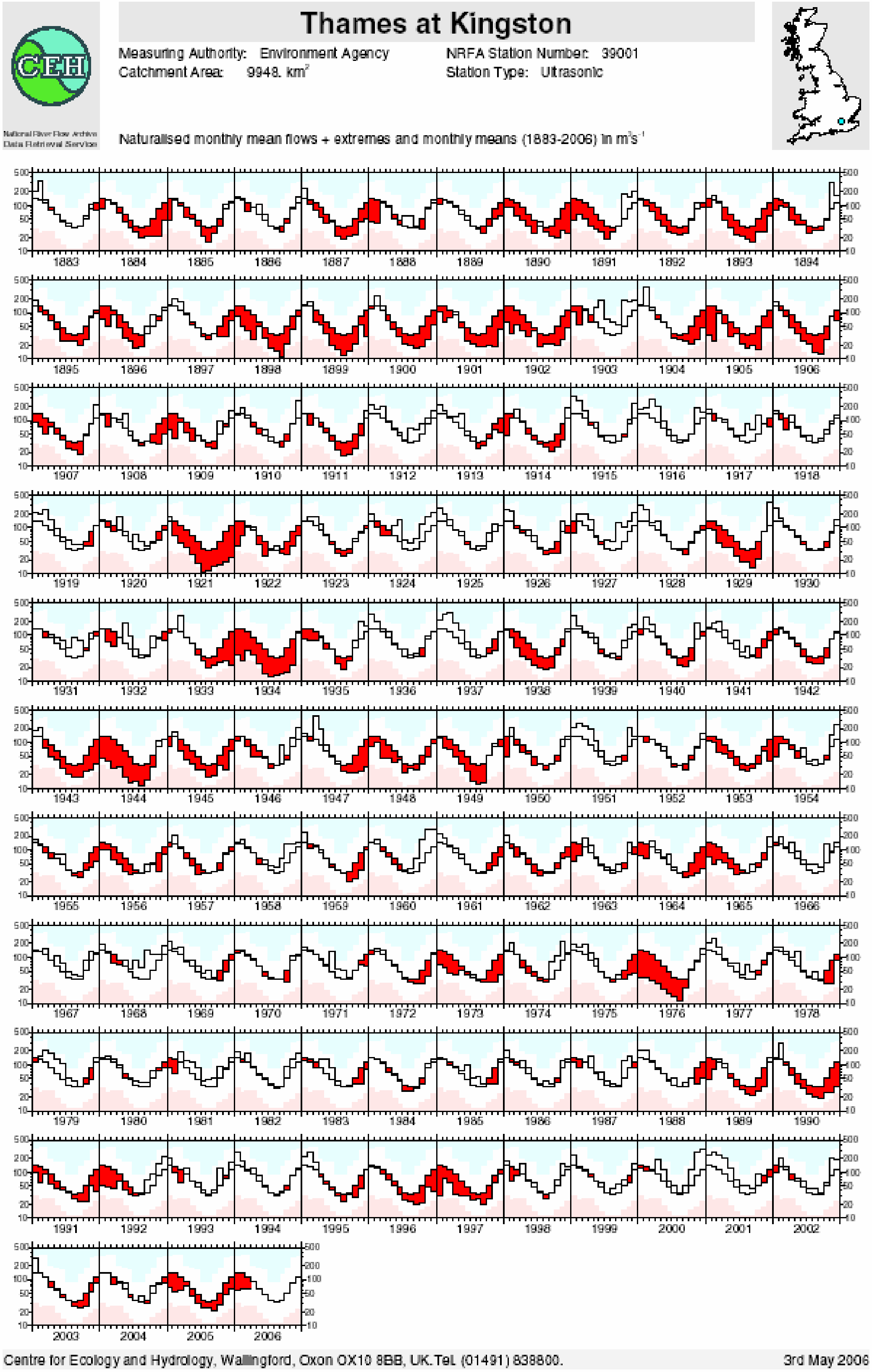
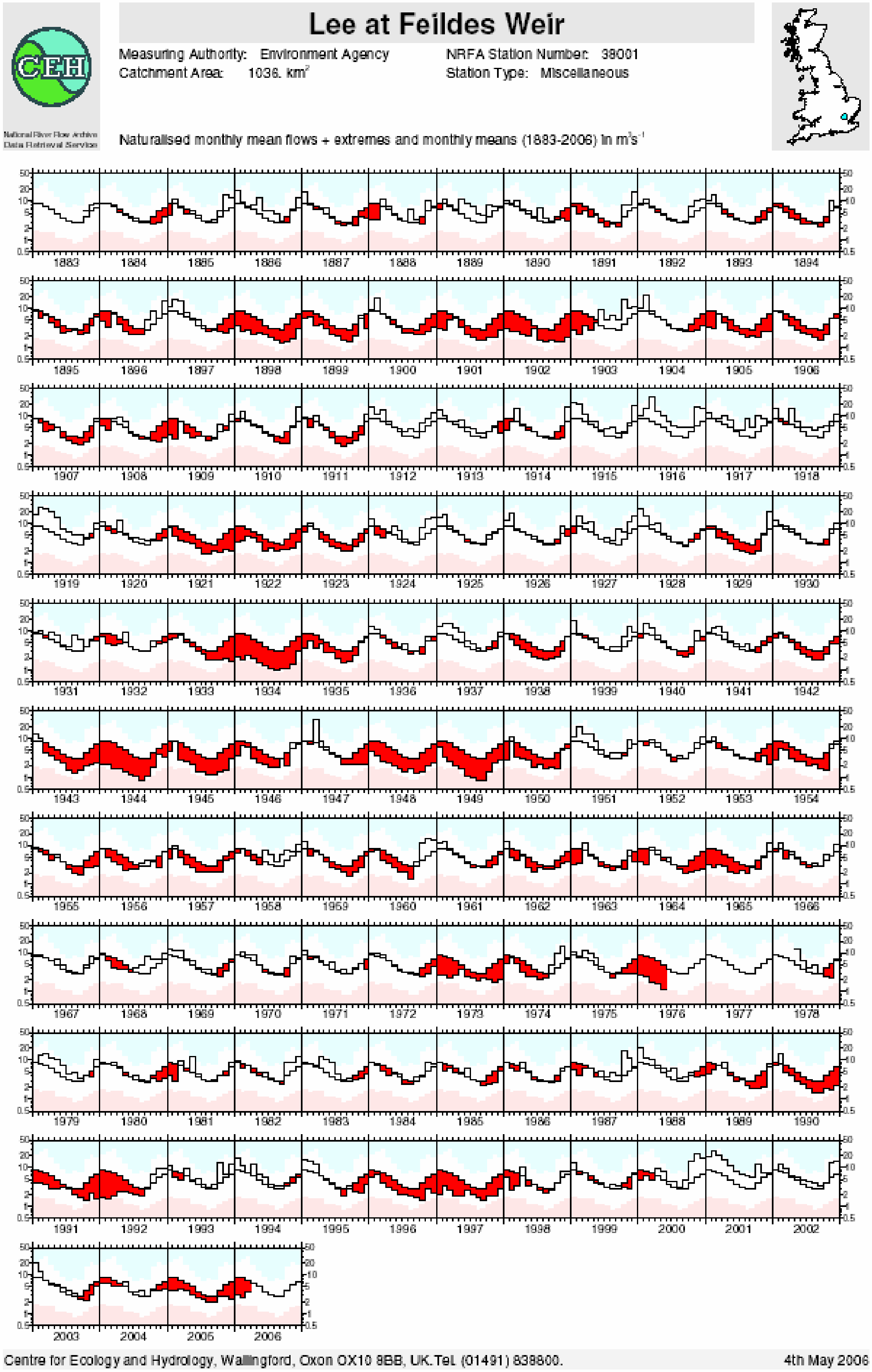
A2: Time series of naturalised monthly flows – Thames at Kingston



A3: Time series of naturalised monthly flows – Lee at Feildes Weir



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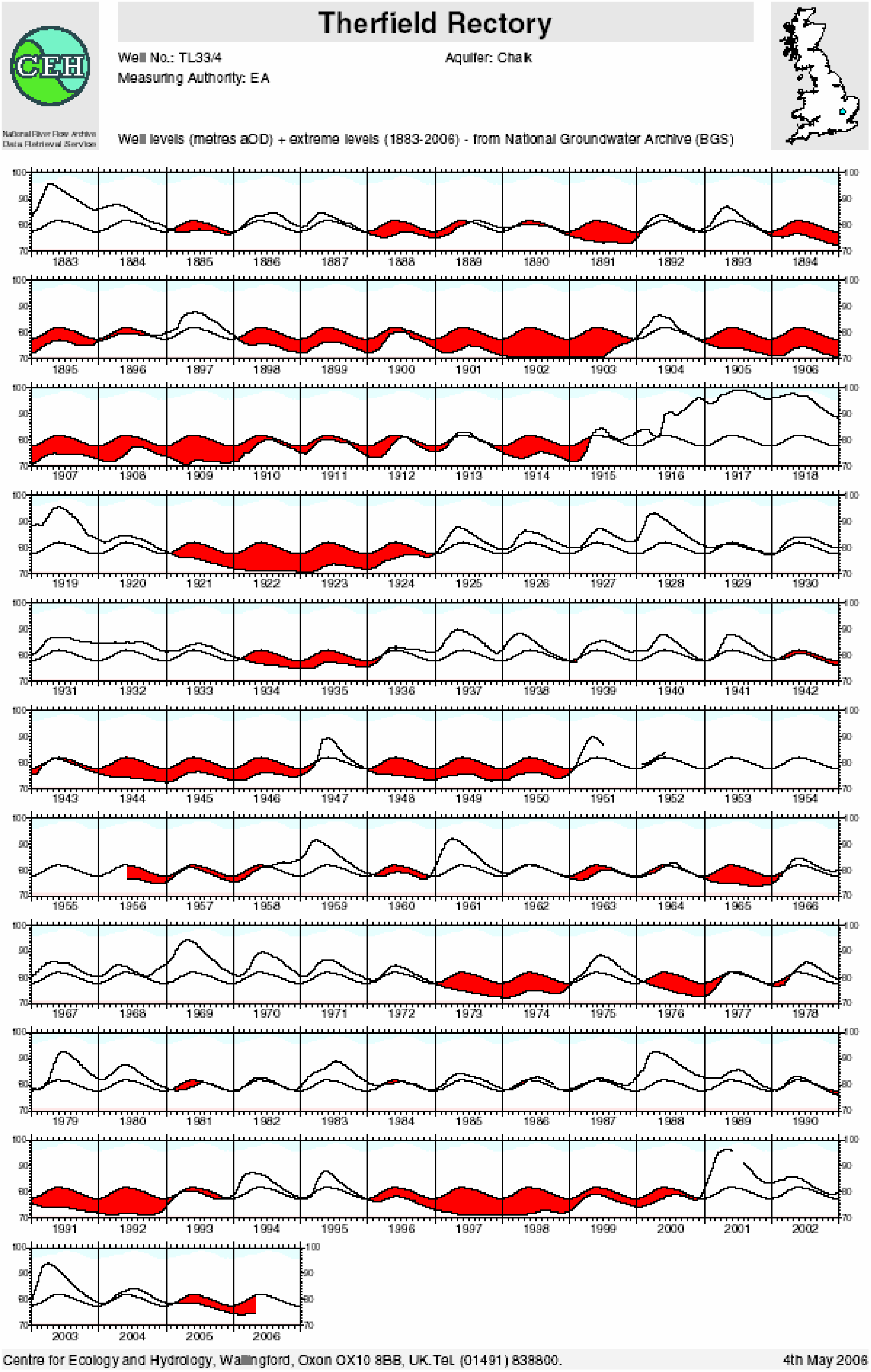
A4: Time series of groundwater levels in Chalk aquifer at Therfield Rectory



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