Interim Report R&D Project 414

Surface Water Yield Assessment (Phase II)

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Interim Report (Phase 2)

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SUMMARY

Following the presentation to the steering group of the Phase I report, the group agreed that Behavioural Analysis was the best approach to the assessment of surface water yields (Ref. Minutes of Steering Group meeting 9.9.92). Phase II of the project thus became an application of this method to stand-alone direct supply reservoirs. The specific terms of reference are given in Chapter 1.

The data sets used in this part of the study were for Vyrnwy, Stocks, Ely Ouse, Exe, Font, Cray, Elan and Taf Fechan. These were all long records, mostly representing the wetter regions of England and Wales, but with Ely Ouse providing data from the drier South East. The records from Vyrnwy, Stocks and Ely Ouse were used in behaviour analyses to examine yield-storage relationships, and the effect of the length of record on those relationships. The data for the Elan, Cray and Taf Fechan, and the reconstructed Exe record were used in a comparison of the severity of the 1933/34 and 1975/76 droughts in the south western area of the country.

The analyses showed the value of behaviour analysis, revealing important facets of reservoir management that would have remained hidden using other assessment techniques. A technique that could be used by water resource practitioners to gain an understanding of the management issues at particular reservoirs was devised, using the relationship between drawdown, critical period and days of storage.

One of the most important issues to emerge was the need for very long records in the behaviour analysis, to cover the period 1880 to 1920, during which long periods of moderately dry years created difficult reservoir management problems.

1. PHASE II TERMS OF REFERENCE AND SCOPE OF STUDY

1.1 Following the Steering Group meeting on 9th September, the Phase II Terms of Reference were defined as follows:

A) A behaviour analysis study on the effect of length of historic record on the relationship between storage and maximum historic yield (without restrictions or seasonal variations) at fixed gross demands from 10% to 90% of ADF for a direct supply reservoir. Data to be used: naturalised monthly flow records at Vyrnwy, Stocks, Font and R. Nene.

Note: NRA Anglia sent data for the Ely Ouse, which was used in place of the R.Nene data. Also, the Font record could not be updated and fully quality controlled in time for this report, so a long "reconstructed" record for the Exe was used instead (see section 3.3).

B) Compare the relative severity of the 1933/34 and 1975/76 droughts in mid/South Wales and SW England for direct supply reservoirs with long critical periods.

C) Investigate the influence of assumptions relating to initial storage in behaviour analysis for direct supply reservoirs.

D) Attempt to identify simple indicators which could be used to assess critical period. Seek to define values of critical period for which yields from behaviour analysis should be backed up by other methods.

1.2 Brief details of the streamflow records used in the study are given in Appendix 1.

1.3 To the reader who is not familiar with the Phase I interim report (Ref 0414/1/N) a brief explanation is needed to put this limited Phase II study into perspective. The first two recommendations in Section 13.2 of the Phase I interim report are as follows:

13.2.1 The recommended method of yield assessment for 'stand-alone' direct supply reservoirs which best satisfies the wide range of requirements set out by NRA is some form of behaviour analysis with long (over 100 year) naturalised flow records, backed up by probability matrix approaches for reservoirs with critical periods substantially greater than 12 months.

13.2.2 The general lack of such long records means that behaviour analysis is often applied to short records in a non-standard manner, perhaps without a proper appreciation of the implications. The revised proposals for stage II should highlight the relative effects of such non-standard use of the technique in respect of the historic yield (without restrictions) for direct supply reservoirs.

1.4 It should be emphasised that this study deals only with predicted yields. The term 'predicted' yield is used in the context of the Phase I Interim Report (section 3.3), ie a calculation that takes no account of standard of service restrictions on demand, or operational assumptions about when the drought will end. 'Predicted' yields are based on analysis of past events, assuming that the usable storage reaches 'empty' on the last day of the low flow sequence, whenever that occurs.

1.5 If a similar study were to be carried out using 'operational' drought assumptions, that the storage must last until (say) the end of November, the 1976 and 1984 droughts (which both effectively ended in early September) would become more severe events, but droughts such as 1959 or 1989 (which ended in late October) would be affected less.

2. BEHAVIOUR ANALYSIS FOR SEMI-INFINITE DIRECT SUPPLY RESERVOIRS AT FIXED GROSS DEMANDS VARYING FROM 10% to 90% OF ADF: EFFECT OF LENGTH OF HISTORIC RECORD ON YIELD-STORAGE RELATIONSHIP

2.1 Method of Calculation

1. The monthly naturalised runoffs in mm, for each of the four study catchments, were assembled on SuperCalc 5 files. The average annual flow (AAF) in mm/yr (and the average daily flow, ADF) were calculated for the period of record, and nine separate gross demands (10% to 90% of the ADF in 10% increments) were initially selected.

2. For each gross demand, the monthly inflow was routed through a semi-infinite reservoir (which can overflow but not empty), assuming the reservoir was initially full. The contents at the end of each month were calculated on the spreadsheet. For each calendar year, the largest storage deficit in mm needed to just meet the specified demand was identified, and then expressed as a percentage of annual average flow.

3. These simple calculations based on monthly inflows do not of course make any allowance for the fact that critical droughts may start part way through the month preceding the first calculated monthly storage deficit, and may end part way through the month following the largest annual storage deficit. Thus, the storage which would be required to satisfy the demands in reality, if the calculations were to be based on a daily behaviour analysis, would be greater than the storage indicated from the monthly behaviour analysis.

   The normal technique for adjusting the monthly results is to add 15 days net storage requirement to the beginning and end of the maximum annual storage deficit (eg Pearson, 1983). However, since this same adjustment would be applied to all the annual maximum storage deficits, and in this study we are only looking for <u>relative comparisons</u> between drought events, no adjustments have in fact been made to the results of the behaviour analysis based on monthly data.

   However, it must be stressed that when <u>actual</u> behaviour analyses are undertaken on specific reservoirs, for the purpose of yield evaluation, they should be based on a daily time-step if daily data are available.

4. The assumption that the reservoir is full at the beginning of each behaviour analysis also needs to be validated. This aspect is dealt with in Section 4.

2.2 Presentation of Results using Standardised Yield Storage Curves

Standardised yield-storage curves express the yield as a percentage of average daily flow (ADF), and the storage as a percentage of average annual flow (AAF).

For each study area, and each incremental value of gross yield, the calendar years in which the largest annual storage deficit occurred were identified, and for each of these events, a standardised yield/storage diagram was plotted for the various demands (see for example Fig 1.1, Vyrnwy). The yield-storage curves for a few additional selected years which gave significant (but not maximum) storage deficits for particular ranges of gross demands could also be added to this type of yield-storage diagrams.

A lower envelope curve can be drawn, which defines the relationship between maximum historic 'Predicted' yield and usable storage for the site, based on a monthly Behaviour Analysis assuming an initially full reservoir.

2.3 Interpretation of Yield-Storage Curves.

The lower envelope curve for the Vyrnwy data (1879-1990) is shown in Fig 1.2. It will be noted from Figure 1.1 that, at a gross yield of around 65% of ADF, the envelope curve is defined by the 1933/34 event, rather than the 1933 event. This reflects the transition from a reservoir which has a critical period less than 12 months, to a critical period greater than 12 months. A further sudden increase in slope will occur when the critical period increases from less than 24 months, to more than 24 months, which occurs at gross yields in excess of 80%.

The basic yield-storage curve can be used in two ways.

i) In initial design, it can be used to estimate the approximate storage required to meet a given gross direct supply yield;

ii) or it can be used to assess the gross direct supply yield of an existing storage.

The remainder of this report is principally directed to use (ii) above, i.e. the effect of length of record upon the assessment of historic yields of existing known storages.

As the purpose of this study is to investigate the effect of length of record on historic yield, return periods have not been calculated for particular sections of the individual yield-storage curves. However, it can be shown statistically that the mean interval (T years) between the lowest n-day flow recorded in an N-year data period is likely to be between 1.5N and 2N, depending upon the assumed distribution for low flow events. On this basis, the lower envelope curve for Vyrnwy is likely to be experienced once every 160 to 220 years on average.

The family of curves in Fig 1.1 can also be used to demonstrate the sensitivity of the yield to estimated return periods, for the location and type of supply system under analysis. For example, the third lowest runoff in a 112 -year record is likely to recur at a mean interval of around 50 years. For a storage of 10% of AAF, 1984 gives the lowest gross yield (37% of ADF), but the next two lowest (1896 and 1933) would give gross yields which are not much greater, at 39% and 40% of ADF respectively.

Thus there is likely to be relatively little difference in yield (around 3% of ADF) between a 1 in 50 and 1 in 200 year drought event for a direct supply reservoir at Vyrnwy with capacity of 10% of AAF. Similar calculations can be made for the lower or higher storage values in Fig 1.1. The precise statistical interpretation becomes more complicated for multi-year drawdowns, but the difference at this site between the third lowest yield and the lowest yield tends to reach a maximum of around 10% of ADF at a storage of 30% of AAF, then diminish to almost zero at higher storages.

Also shown on Figure 1.1 is the 2% yield-storage curve independently derived by North West Water.

It is worth noting, in passing, that the lower end of the yield-storage curve also identifies the contribution of minimum flows from natural storage (soilwater, groundwater) in maintaining gross yield. The intercept on the Y-axis is the minimum natural monthly flow (the yield with zero artificial storage).

2.4 Behaviour Analysis for Vyrnwy: 1879 to 1990

Table 1 shows the years in which the five greatest storage deficits occur, for each of the demand values. The worst drought events in the 112-yr record (for a direct supply reservoir with uniform drawoff and storage up to 80% of AAF) are seen to be 1976, 1984, and 1933/34.

Table 1 shows that, at demands of 90% of ADF, the worst drawdowns would all occur in the period 1902 to 1911. These would be part of a continuous drawdown period for Vyrnwy lasting over 30 years, from February 1887 to January 1928, which would require storage of 142% of AAF to maintain the yield of 90% of ADF.

Extremely long drawdown periods, lasting over several years, are likely to generate 'temporary' conservation measures (hosepipe bans, drought orders) lasting for long periods. North-West Water has decided to limit the defined gross yield of its direct supply reservoirs to a value (assessed as 76% of ADF) which limits drawdown periods to a maximum of around five years. At a gross yield of 80% of ADF, the longest drawdown periods at Vyrnwy would be March 1887 to Dec 1891, and April 1933 to December 1936.

The "worst" yield-storage curves for individual years of the Vyrnwy record (Fig 1.1) are used to define the lower envelope curve (Fig 1.2) for different values of gross yield and usable storage.

Thus, for storages up to 5% of AAF, it is 1976 which produces the minimum historic yield. For storages in the range 5% to 16% of AAF, 1984 is the worst event. For storages in the range 15% to 50% of AAF, 1933 and 1933/34 are the worst historic events.

The Vyrnwy record is one of the few which goes back before 1920. It is therefore particularly important to note that the period between 1887 and 1920 appears to define the lowest historic yield for direct supply reservoirs taking a high yield (over about 80% of ADF); but for direct supply reservoirs with gross yields of 80% or less of ADF, the 1887 to 1932 data does not influence the minimum yield-storage curve derived from the shorter 1933 to 1990 data period.

2.5 Stocks Reservoir, 1927 to 1990

Table 2 shows the years in which the five greatest storage deficits occur, for each of the demand values. The worst drought events in the 64-yr record (for a direct supply reservoir with uniform drawoff and storage up to 80% of AAF) are seen to be 1940, 1959, and 1933/34.

Figure 1.3 shows the individual yield-storage curves for the Stocks data for 1940, 1959, and 1933/34. These three events give the worst drawdowns at Stocks for all yields. The breakpoint between 1959 and 1933/34 occurs at a gross yield of 65% of ADF (gross storage 21% of AAF).

The return period of the worst event in the 64-year data period is likely to be between 100 and 130 years. Examination of the sensitivity of the yield to return period (as in 2.3 above for Vyrnwy) indicates that the difference in yield between the worst event and the 2nd worst event (1 in 40 yrs approx), is generally less than 2% of ADF, except at storages greater than 70% of ADF.

2.6 Ely Ouse, 1933 to 1990

Being a lowland river, the Ely Ouse flows through topography which is unsuitable for the construction of a direct supply reservoir. Nevertheless, the yield storage curves for a hypothetical direct supply reservoir have been derived, to give a comparison with the Stocks and Vyrnwy data, for gross demands up to 80% of ADF.

The individual yield-storage curves for the worst events are shown in Fig 1.4. It is immediately evident that, for all but the highest gross demands, the period 1934 to 1935 dominates the minimum yield-storage curve, with 2 and 3-year critical periods (1933-35) determining yields of more than 60% of ADF.

For storages up to 18% of AAF, 1934 is the worst event. From 18% to 50% of AAF, 1933/34 takes over. For storages above 40% of AAF, 1933/35 is the worst event. For storages greater than 110% of AAF (not shown), 1949/50 takes over as the worst event.

The return period of the worst event in the 58-year data period is likely to be between 90 and 120 years. Examination of the sensitivity of the yield to return period (as in 2.3 above for Vyrnwy) indicates that the difference in yield between the worst event, and 3rd worst event (1 in 20 year approx), is between 5% and 10% of ADF, depending on the storage selected.

2.7 Comparisons between results.

Figure 1.5 shows the minimum yield-storage curves for Vyrnwy, Stocks and Ely Ouse plotted on the same axes, with an upper limit of gross yield of 80% of ADF. Within this range, the Vyrnwy curve is no different from that which would be derived for 1927-90 (or 1933-90), so the differences in the three curves are not related to differences in the record periods used. Also shown is the minimum yield-storage curve for Fontburn reservoir (1909-

1991), calculated on the same basis by Northumbrian Water.

The Stocks curve generally lies slightly above that for Vyrnwy. There has been insufficient opportunity to investigate the reasons for this difference, but North-West NRA or North-West Water may have some suggestions. The Fontburn curve is slightly lower then the Vyrnwy curve, but higher than the Ely Ouse curve.

The Ely Ouse curve lies significantly below both the other three curves, for all gross yields and storages. At low and medium demands, this is perhaps initially a surprise, as the Ely Ouse might be expected to have better low flow characteristics. However, whilst 1959, 1976 and 1991 generally define the the worst events at Stocks, Vyrnwy and Fontburn respectively, it is the 1934 low flows which determine the lower values of the Ely Ouse curve. Whereas the winter rainfall of 1933/34 would have eradicated any soil moisture deficits in the shallow upland soils of Vyrnwy and Stocks, it is probable that 1933/34 winter rainfall in the Ely Ouse would have been insufficient to fully eradicate the higher soil moisture deficits, and recharge groundwater. This would explain why the Ely Ouse streamflows in Spring 1934 were so unusually low, and why 1934 defines the minimum yield-storage curve at low demands.

This demonstrates quite clearly the potential errors in trying to use 'standardised' yield-storage curves in areas which are not hydrologically homogeneous. The Institute of Hydrology study in Ireland (see D3 of Project Record Vol.1) also exhibits significant variations between yield-storage relationships for different locations.

2.8 Effect of Length of Historic Record on Yield-Storage Relationship

The Vyrnwy behaviour analysis over the period 1879 to 1990 shows that, for a direct supply reservoir with uniform demand in this region, with relatively little natural soilwater storage and no groundwater:

i) gross yields of 90% of ADF are determined by long sequences of dry years in the period 1887 to 1928. If multiple-year drawdowns are to be avoided, gross predicted yields should be limited to around 75% of ADF. This does not preclude overdrawing in non-critical years, based on appropriate control rules.

ii) for usable storage less than 5% of AAF, 1976 is the worst (or equal worst) drought event in the 1879 to 1990 period

iii) for usable storage between 5% and 16% of AAF, the minimum yield storage curve in the 112-year record is defined by the 1984 drought event

iv) for usable storage of 16% to 54% of AAF, 1933/34 is the worst historic event, and an historic record from 1933 onwards would have produced the same historic minimum yield-storage curve as 1879-1990.

The Stocks behaviour analysis over the period 1927 to 1990 shows that:

i) for usable storage less than 2% of AAF, 1940 is the worst drought event in the 1927 to 1990 period

ii) for usable storage between 2% and 21% of AAF, the minimum yield storage curve in the 64-year record is defined by the 1959 drought event

iii) for usable storage of more than 21% of AAF, 1933/34 is the worst historic event.

The Ely Ouse behaviour analysis shows that the minimum historic yield is associated with the 1933/34/35 drought event at all demands up to 80% of ADF. For usable storage up to 50% of AAF, the lowest storage deficits would occur in 1934. This is attributed to extreme low river flows consequent upon lack of full recharge of soil moisture and groundwater during the winter of 1933/34.

Whilst the 1933/34/35 drought is clearly dominant for the Ely Ouse area (at all demands up to 80% ADF) and for Stocks and Vyrnwy at demands between 50% and 80% of ADF, there is some evidence that the 1975/76 drought was more severe at higher demand levels in South Wales. Accordingly a more limited series of behaviour analysis studies were undertaken to investigate this, as described in Section 3 below.

3. COMPARISON OF SEVERITY OF 1933/34 and 1975/76 DROUGHTS IN MID/SOUTH WALES AND SOUTH-WEST ENGLAND FOR DIRECT SUPPLY RESERVOIRS WITH LONG CRITICAL PERIODS AT FIXED GROSS DEMANDS

3.1 Method of Calculation

Data from Elan, Cray and Taf Fechan were added to the analysis to give a fuller picture for the Welsh region. The method of calculation is the same as described in 2.1. However, as some of these flow records were only available up to the end of 1976 or 1980, only the 1975/76 and 1933/34 yield-storage curves are compared in Table 3, for storages of 15% or more of AAF. Table 3 shows the year in which the maximum storage deficit (lowest yield) occurred for the period of record.

3.2 Comparison of Results for Vyrnwy, Elan, Cray, Taf Fechan

Table 3 confirms that, in parts of South Wales at least, 1975/76 produced lower yields than 1933/34 for situations where usable storage was 20% or more of AAF. The differences were not always large; the yield storage curves for storages greater than 20% of ADF tended to run roughly parallel, with the 1976 yield becoming smaller than the 1934 yield the further south the location:

Vyrnwy:	1976 higher than 1934 by around 9% of ADF
Elan:	1976 higher than 1934 by around 2% of ADF
Cray:	1976 lower than 1934 by around 2% of ADF
Taf Fechan:	1976 lower than 1934 by around 6% of ADF

Investigation of monthly runoff records shows extremely high values at Cray and Taf Fechan in October 1933, which would appear to have ameliorated the effects of the 1933/34 drought event in parts of South Wales. The next question is, which is the more severe event in SW England?

3.3 South-West England - the River Exe Reconstructed Record.

Unfortunately, there is a shortage of long continuous flow records in South-West England. However, Jones, Ogilvie and Wigley (1984) have published a reconstructed flow record for the Exe at Thorverton from 1856 to 1956, based on the measured record from 1957 to 1979; this data was published as part of a study to derive long flow records for 10 catchments in England and Wales.

The pre-1957 flow data was derived using an empirical rainfall-runoff model developed in 1978 at the Central Water Planning Unit. In the case of the Exe, there are 6 terms in the regression, which indicates a comparatively short catchment 'memory'; by comparison, the

Ouse record at Denver Sluice, which they also extended, has 11 terms in the regression.

The calibration period used for the Exe regression was 1958 to 1977, which included some notable drought events; the verification period is quoted as being 1907 to 1911, which does not appear to make sense. Before confirmation of any conclusions from the reconstructed Exe data, the outputs of the regression equation for 1978-90 should be compared with the recorded data for this period (not possible when the data was published in 1984). The following comments on the results of the behaviour analysis of the reconstructed Exe flow must therefore be provisional.

The standardised yield-storage curves for the worst events in the 1856 to 1979 period are shown in Fig 1.6, for yields up to 90% of ADF. The reconstructed Exe data shows, even more clearly than the Vyrnwy data, the excessive drawdowns which occur during a long series of years with lower than average runoff in the 1887 to 1913 period. Annual maximum storage deficits in these years fix the yield-storage curve onto a virtually horizontal line for demands greater than 80% of ADF.

For example, at a demand of 90% of ADF, a reservoir on the Exe would be drawn down for a 20-year period (March 1884 to Feb 1904) followed immediately by a 10 year period (March 1904 to Feb 1913). Even at a demand of 80% of ADF, the reservoir would be continually drawn down from Jan 1887 to March 1894, and from March 1904 to Feb 1910. By contrast, at 80% of ADF in 1933/34, the drawdown period would be only March 1933 to December 1935.

The reconstructed Exe data indicates that 1921 is the drought event which produces the largest drawdowns in the 1856-79 period, for direct supply storages between 5% and 25% of AAF. For larger storages between 25% and 50% of AAF, the 1933/34 event produces the maximum drawdowns (in 1934).

For the Exe reconstructed data, and direct supply reservoirs with storage less than 20% of AAF, the 1921 event gives yields which are lower than the 1975/76 yields, by up to 8% of AAF. The drought events associated with 1869/70 and 1887/88 both appear to be worse than 1975/76 for this range of direct supply storages.

It is noted from the Project Record Volume 1 (Item C1) that behaviour analysis studies on the Thames rank the 1921 drought (with 1976), as the most severe events after 1933/34, in relation to the minimum yield for the pumped storage reservoirs on the Thames, for the data available from 1920 onwards.

4. INFLUENCE OF ASSUMPTIONS RELATING TO INITIAL STORAGE IN BEHAVIOUR ANALYSIS FOR DIRECT SUPPLY RESERVOIRS

4.1 Assumptions of initial storage full

McMahon and Mein (1986) point out that behaviour analysis usually starts with the assumption that the reservoir is initially full, and that such an assumption needs to be checked. They also suggest that there may be potential dangers in using broken periods of record for behaviour analysis. These concerns are certainly relevant in respect of some climatic regions, but how far are they relevant to the predominantly temperate climate of England and Wales?

Behaviour analysis, using long flow records, is itself a useful way of investigating these concerns. Clearly, if a UK direct supply reservoir is of such a limited size that it always refills after a summer drawdown, before the start of the following summer, then the assumption of a full reservoir (depending upon when impounding starts for a new reservoir), in behaviour analysis with individual drought events to estimate yield, is also valid.

For this study of direct supply reservoirs, the behaviour analyses for the runoff records at Vyrnwy, Stocks and Ely Ouse were used. For each of the demand levels (10% to 80% of ADF), the years when the semi-infinite reservoir was <u>not</u> full on 1st April were identified, and the critical periods (in months) for the five worst drought events (time from start of drawdown to lowest storage) were also calculated.

Figure 2.1 shows the percentage of years full on 1st April against Gross Yield as percentage of ADF for Vyrnwy, Stocks and Ely Ouse. It will be noted that, even at quite small gross yields (less than 40% of ADF), it is not certain that a reservoir would be full on 1st April. For drawoffs of 50% of ADF, the chance of being full on 1st April drops to between 70% and 85%. For drawoffs of 75% of ADF (the suggested maximum value to avoid multi-year drawdown sequences) the chance of being full on 1st April drops to between 50% and 55%.

Figure 2.1 clearly demonstrates that in many cases the uncritical assumption of a full reservoir at the start of a behaviour analysis is not justified. It is therefore recommended that UK behaviour analyses start on an appropriately selected date in the autumn of year 1 (eg, 1 November), with initial storage equal to a specified minimum reserve at that date.

4.2 Maximum drawdown periods

The behaviour analyses for semi-infinite direct supply reservoirs using Vyrnwy and Exe data have clearly identified the multi-year drawdown periods which occur in the forty years prior to 1920, for gross yields in excess of 75% to 80% of ADF. Behaviour analyses based only on post-1920 data would not have identified such severe sequences, which cause the yield-storage curves to tend towards a horizontal line.

Figure 2.2 shows the maximum drawdown periods (in months) for the Vyrnwy, Stocks, Ely Ouse and Exe behaviour analyses; the Font data (provided by J. Mawdsley) are also included. The X-axis is here expressed in 'number of days storage at lowest historic yield', which is obtained by dividing the storage (as % of AAF) by the gross historic yield (as % of ADF) and expressing the answer in days. It will be noted that the maximum drawdown exceeds 12 months when the number of days storage exceeds 75 days approximately.

For maximum drawdown periods greater than 24 months, the Vyrnwy data is dominated by the pre-1927 data. Because the Stocks record does not commence until 1927, its worst event is the 1933/35 drought. The decision adopted by North-West Water, to limit yields of direct supply reservoirs to around 75% of ADF, is based on the longer Vyrnwy record.

5. CRITICAL PERIODS

5.1 Introduction

The terms of reference require that the study attempts to identify simple indicators which could be used to assess critical period, and seeks to define values of critical period for which yields from behaviour analysis should be backed up by other methods.

Although most water resources engineers and hydrologists are broadly aware of the approximate critical periods of their water resources systems - usually expressed broadly in terms of 1 or 2 year critical - such figures are not normally linked to the officially quoted yield of the system. Because yields are based on rare events, often outside the experience of individuals currently operating the systems, operators cannot always appreciate, simply from the stated figure for yield, how a particular system may behave in a severe drought event.

If the stated yield for a surface water resource system were to be accompanied by the figures for the corresponding critical period (in months) and maximum drawdown period (in months or years), there may be a better general appreciation of the characteristics of the resource, and whether it is vulnerable to short or long drought events. This information would be important for management issues, and practical considerations relating to the imposition of water conservation measures.

An attempt was made, using the Stocks, Vyrnwy, Ely Ouse, Exe and Font data, to relate critical period to storage. For each site, for various demands, the drought events which produced the largest drawdowns were identified, and the corresponding critical periods identified (to 1 month discrimination). These are listed in Table 4 to Table 8, and plotted in Fig 2.3., with the X-axis in 'number of days storage at lowest historic yield', which is obtained by dividing the storage (as % of AAF) by the gross historic yield (as % of ADF) and expressing the answer in days. Also shown is the upper envelope curve of the maximum drawdown period, taken from Figure 2.2.

5.2 Critical Period as a Function of Storage

Fig 2.3 indicates that critical period can be approximately assessed from storage (expressed in days). If storage is less than 75 days, the reservoir will have a critical period of 5 months or less, and will always (in the historic period, at least) refill by the following Spring.

If storage is between 75 and 130 days approx, the critical period will always be less than 12 months, but there will be occasions when the reservoir fails to refill by the start of the next year, or even occasionally the year after that. However, the maximum drawdown in the 2nd or 3rd years will not be as severe as in the first year.

If storage is between 130 and 170 days, the worst drought event could have a critical period of either 9 or 18 months. If storage is between 170 and 250 days, the critical period will be approximately 18 months.

However, if a criteria of 5 years maximum drawdown period is applied (as with North-West) this could imply a limit of around 190 days storage.

5.3 Management Implications of Derived Critical Period/Storage Relationship

The derived relationship in Fig 2.3 is only based on data from five sites across the country. If it is reasonably valid for other existing direct supply reservoirs, it could be used to draw some useful generalised conclusions for management of direct supply reservoirs at fixed gross yields, when used in conjunction with storage-yield diagrams such as Figure 1.5.

The storage in days can be represented on the storage-yield diagram by a series of straight lines passsing through the origin. Fig 2.4 shows three key lines (75 days, 150 days and 190 days) superimposed on Figure 1.5, with appropriate text.

If storage is less than 75 days, the average critical period in the worst drought will be 5 months or less, but the direct supply reservoir would always refill by the following Spring. For such small 'stand-alone' reservoirs, it is simply not feasible to obtain (and effectively implement) meaningful temporary water conservation measures in summer through the Drought Order procedures. In such situations it would be sound management practice to specify abstractions and compensation water releases which vary with reservoir storage during the summer/autumn, based on behaviour analysis studies.

For storage between 75 and 130 days the critical period in the most severe drought will not exceed 12 months, but drawdown may last for up to 36 months. For this range of storage, winter conservation measures (or enhanced refill arrangements) will provide a "comfort" factor, but will not increase the yields significantly.

For storage in the range 130 to 170 days, critical periods may be either one-summer or two-summer, and behaviour analysis will be needed to determine which one is relevant to the site.

For storages of over 170 days, regular winter conservation measures (enhanced refill arrangements) could significantly increase yields.

For storages in excess of around 200 days, limitations on maximum drawdown period (rather than storage provided) may become the limiting factor on yield, as long drawdown periods are likely to lead to long periods of restrictions, which will influence standards of service.

These provisional conclusions will of course need to be checked at other sites, but their incorporation into the sample storage/yield graph does give some useful indicative guidance on management implications.

5.4 Other Methods to Back-up Behaviour Analysis

The Vyrnwy and Exe data, pre 1920, have shown how important it is to have some long records (greater than 100 years) for water resources systems which seek to utilise a high percentage of long-term average runoff. The period 1880 to 1920 appears to have a very severe cumulative drawdown effect on large direct supply reservoirs (drawoff greater than

75% of ADF). A practical solution (used by North-West) is to introduce a constraint that the yield of such reservoirs should be restricted to around 75% of ADF, so that no direct supply reservoir should be continually drawn down for more than 5 years.

The reconstructed flow records for 10 catchments in England and Wales (Jones, Ogilvie and Wigley, 1984) are a valuable source of data for developing limiting guidelines of this type. It would be advantageous if the predicted values from 1979 to date could be calculated and the results compared with measured data for these 10 sites since 1979; this would give more confidence in the early reconstructed records, and allow all ten records to be used for studies such as the one undertaken in this report.

In the absence of this long-term data, no recommendations can yet be made as to back-up methods for behaviour analysis for systems with long critical periods. The alternative, and simpler approach, is to introduce limitations on maximum duration of drawdown.

6. CONCLUSIONS

6.1 Direct Supply Reservoirs Operated At Fixed Gross Yields

The following conclusions, based on the limited number of sites used in the analysis, relate to direct supply reservoirs operated at fixed gross yields.

1. The Vyrnwy and Exe (reconstructed) records both indicate that yields of more than about 75% of ADF are significantly and adversely influenced by a long series of moderately dry years between 1880 and 1911, which produce multi-year drawdown periods. The following conclusions are therefore based on the over-riding premise, currently used by North-West Water, that direct supply yields should be limited to a maximum of 75% of ADF, even if storage is apparently sufficient to maintain higher yields in the post 1920 period.

2. The Steering Group will need to consider:

   a) if guidelines such as the '75%' rule should be incorporated into standard methods of yield assessment of direct supply reservoirs which are based on behaviour analysis from 1920 onwards. There could be a caveat that any behaviour analysis which seeks to justify a higher yield must be proven on a behaviour analysis from 1880. Other types of resources systems would need other limiting guidelines.

   or

   b) if the criterion for historic yield should be based on a period from 1880 to date, rather than 1920 to date.

3. It can reasonably be assumed that this long dry period around the turn of the century has no influence on the yields (for all storage sizes up to around 200 days gross yield) which would be calculated by behaviour analysis for 1920 onwards, for the Exe, Cray, Taf Fechan, Elan, Vyrnwy and Stocks sites. This conclusion could be checked at other sites around England and Wales, using the reconstructed records at 9 sites (Jones, Ogilvie and Wigley, 1984) updated to 1990.

4. 1933/34 is the definitive drought for all sizes of reservoir for the Ely Ouse record, which starts in 1933. It is also the definitive drought for the larger storages, for all sites investigated except in South Wales, where 1975/76 is the definitive event. The definitive droughts for direct supply reservoirs on the main sites investigated are as follows:

Site	Storage as % of AAF	Definitive Drought	Comments
Stocks:	Less than 2%	1940	
(1927-90)	2% to 21%	1959	
	21% to 43%	1933/34	
Vyrnwy	Less than 16%	1976	
	16% to 26%	1933,	
(1879-90)	26% to 50%	1933/34	
Exe	Less than 4%	1869	Post 1979
(reconstructed)	4% to 27%	1921	to be
(1856-1979)	Over 27%	1933/34	checked

5. The above table shows that, if 'historic' yield was calculated using behaviour analysis with data from 1920 onwards, there would be negligible difference in minimum historic yield, compared to an analysis using longer records from 1879 onwards for the sites shown.

6. Figures such as 1.1, 1.3, 1.4 and 1.6 can be used to estimate the amount (in terms of % of ADF) by which the yield for the worst historic event exceeds the yield for the 2nd, 3rd or 4th worst event. Often, the differences are quite small (only a few % of ADF).

7. The assumption generally used in behaviour analysis, that reservoirs are full when simulation studies are started, is not strictly true even at drawoffs of only 30% of ADF. At drawoffs of 75% of ADF, it is clearly inappropriate. It is therefore recommended that UK behaviour analyses start on an appropriately selected data in the autumn of Year 1 (eg 1 November) with initial storage equal to a specified minimum reserve at that date.

8. The study has, using records from five sites, produced a draft relationship (Fig 2.3) between maximum drawdown period, critical period and number of days storage. If confirmed by checks at other sites, this is thought to be useful as a simple guide to management strategies of individual reservoirs.

6.2 Other Fixed Gross Yields for Direct Supply Reservoirs

It must be remembered that the worst historic droughts identified in this analysis take no account of the assumptions or restrictions which would occur in real-time operation. Further analyses would be needed to define the 'Standard of Service' yield, or the 'Operational Yield' (see Phase I Report for definitions).

6.3 Definitive Droughts for Other Types of Resources

It must also be appreciated that for other types of resources (eg regulating reservoirs) the most critical sequences in the historic record will not necessarily be the same as those for the predicted yields of direct supply reservoirs, and further analyses would be needed to define the worst relevant droughts.

TABLE 1: **Vyrnwy Monthly Behaviour Analysis 1879 to 1990 Direct Supply Reservoir With Fixed Gross Yield. Predicted Yields, No End-Date Corrections**

YEARS OF GREATEST STORAGE DEFICITS (RANK 1 = LARGEST)
* indicates failure to refill in previous winter

GROSS YIELD as-%-of-AAF	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
10%	1976	1896	1933	1895	1919
20%	1976	1984	1933	1955	
		1896		1901	
30%	1984	1896	1976	1933	1989
40%	1984	1933	1896	19761	1989
50%	1984	1933	1896	1937	1976
60%	1933	1984	1934*	1937	1896
70%	1934*	1933	1984	1937	1896
75%	1934*	1933	1984	1888*	1976*
80%	1934*	1935*	1933	1976*	1888*
90%	1911*	1912*	1909*	1902*	1910*

TABLE 2: Stocks Behaviour Analysis 1927 to 1990 Direct Supply Reservoir With Fixed Gross Yield. Predicted Yields, No End-Date Corrections

YEARS OF MAXIMUM STORAGE DEFICITS (RANK 1 = LARGEST)
* indicates failure to refill in previous winter

GROSS YIELD as % of AAF	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
10%	1940	1955	1978	1947	1980
20%	1959	1978	1976	1940	1941
30%	1959	1978	1976	1949	1984
40%	1959	1949	1984	1978	1976
50%	1959	1937	1949	1984	1989
60%	1959	1937	1949	1984	1989
70%	1959	1937	1933	1984	1949
80%	1934*	1933	1959	1937	1984
90%	1934*	1933	1959	1937	1956*

TABLE 3: Year In Which Maximum Storage Deficit Occurred For Stated Value Of Storage

	STATED VALUE OF STORAGE AS % OF ADF							
	15%	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
Vyrnwy 1879-90	33	33	33	34*	34*	34*	34*	34*
Elan 1908-76	76	76	34*	34*	34*	34*	34*	34*
Cray 1921-76	33	76*	76*	76*	76*	76*	76*	76*
Taf Fechan 1913-83	76	76*	76*	76*	76*	76*	76*	76*

* events with critical period more than 12 months

TABLE 4: Critical Periods for Worst Historic Droughts at Vyrnwy, 1879-1990

(1) Gross Yield as % of ADF	(2) Max Storage Deficit as % of AAF	(3) Year of Event	(4) Storage in Days *	(5) Critical Period (months)
10	0.90	1976	33	2
20	3.33	1976	61	3
20	3.33	1896	61	3
30	6.84	1984	83	4
40	11.1	1984	101	5
50	16.0	1984	117	6
60	23.4	1933	142	9
70	35.2	1934	183	18
75	42.7	1934	208	18
80	50.2	1934	229	18
90	141.6	1911	574	294

* Storage in days = 365 x (2)/(1)

TABLE 5: Critical Periods For Worst Historic Droughts at Stocks, 1927-1990

(1) Gross Yield as % of ADF	(2) Max Storage Deficit as % of AAF	(3) Year of Event	(4) Storage in Days	(5) Critical Period (months)
10	0.38	1940	14	1
20	2.55	1959	47	2
30	5.41	1959	66	5
40	9.40	1959	87	5
50	13.6	1959	99	5
60	18.5	1959	112	8
70	29.4	1934	153	17
80	43.3	1934	198	17
90	58.9	1934	238	18

* Storage in days = 365 x (2)/(1)

TABLE 6: Critical Periods for Worst Historic Droughts at Ely Ouse

(1) Gross Yield as % of ADF	(2) Max Storage Deficit as % of AAF	(3) Year of Event	(4) Storage in Days	(5) Critical Period (months)
10	2.3	1934	83	3
20	6.2	1934	113	5
30	10.95	1934	133	6
40	18.4	1934	168	17
50	33.4	1934	243	17

TABLE 7: Critical Periods for Worst Historic Droughts at Exe

(1) Gross Yield as % of ADF	(2) Max Storage Deficit as % of AAF	(3) Year of Event	(4) Storage in Days	(5) Critical Period (months)
20	3.78	1870	69	4
		1921		5
30	7.95	1921	97	5
40	12.68	1921	116	6
50	18.2	1921	133	7
60	24.6	1921	150	10
	24.6	1934	150	17
70	39.6	1934	206	18
80	54.6	1934	249	18
90	105.4	1896	427	114

TABLE 8: Critical Periods for Worst Historic Droughts at Font

(1) Gross Yield 98% of ADF	(2) Max Storage Deficit as % of AAF	(3) Year of Event	(4) Storage in Days	(5) Critical Period (months)
20	6.0	1991	110	6
30	11.1	1991	136	7
40	17.0	1991	155	7
50	22.8	1991	166	7
60	32.8	73	196	19
70	56.1	74	293	29

Figure 1.1 YIELD STORAGE RELATIONSHIPS
VYRNWY RESERVOIR 1879–1990
Based on behaviour analysis using monthly data.
uncorrected for end effects

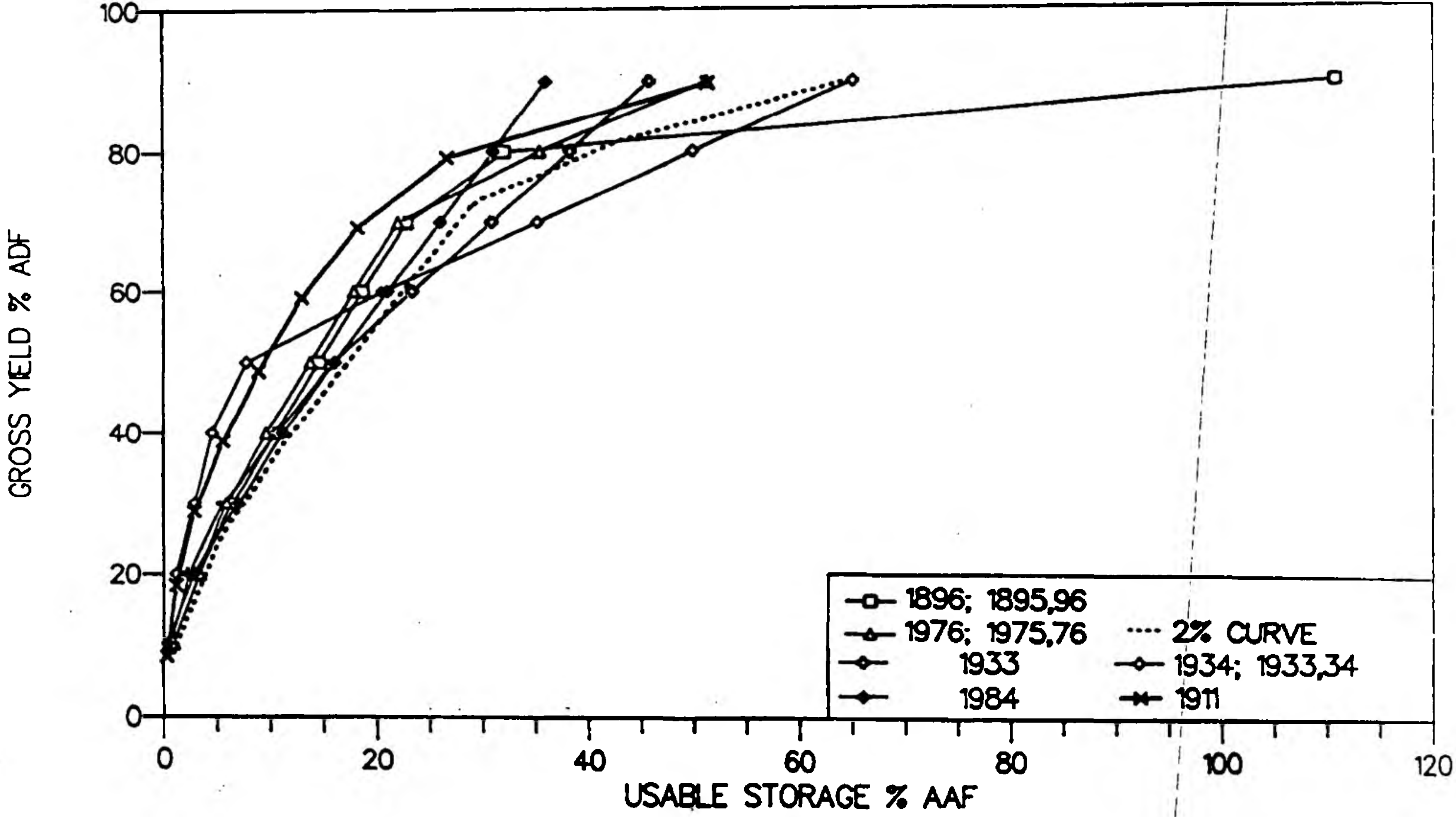


Figure 1.2 MINIMUM YIELD STORAGE RELATIONSHIP
VYRNWY RECORD 1879–1990
Based on behaviour analysis using monthly data.
uncorrected for end effects

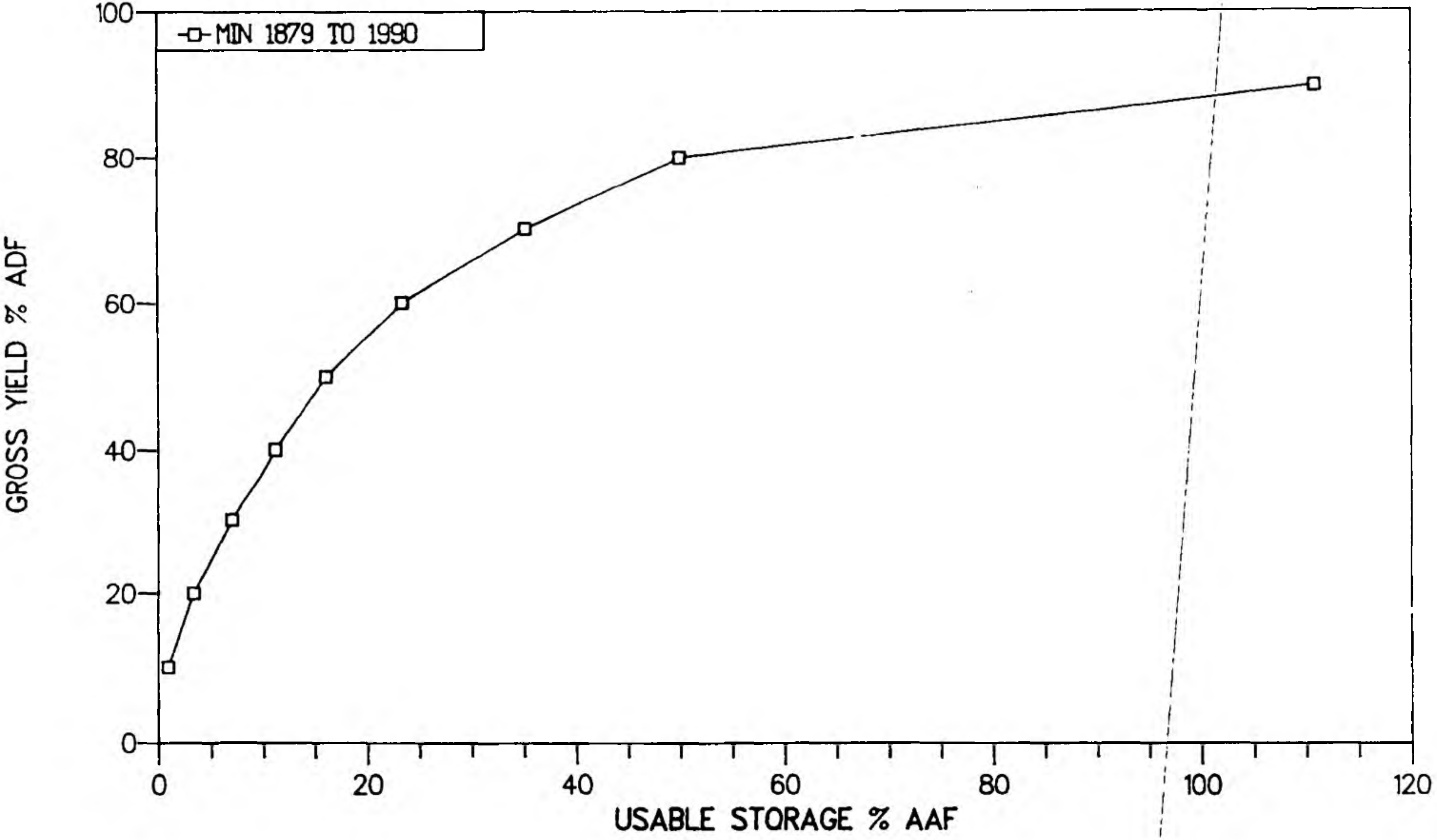


Figure 1.3 YIELD STORAGE RELATIONSHIPS
STOCKS RESERVOIR 1927–1990

Based on behaviour analysis using monthly data.
uncorrected for end effects

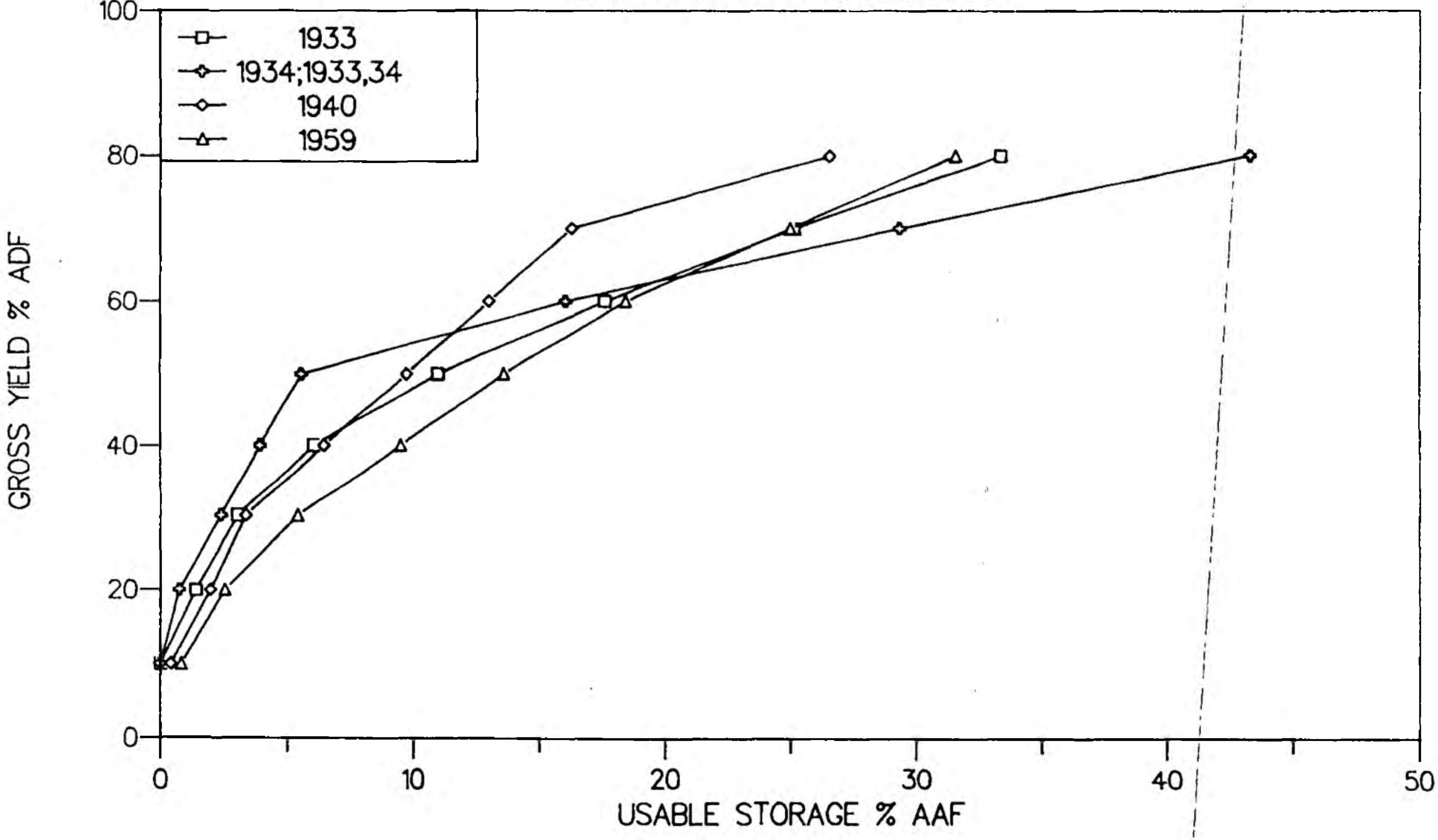


Figure 1.4 YIELD STORAGE RELATIONSHIPS
ELY OUSE RECORD 1933–1990
Based on behaviour analysis using monthly data.
uncorrected for end effects

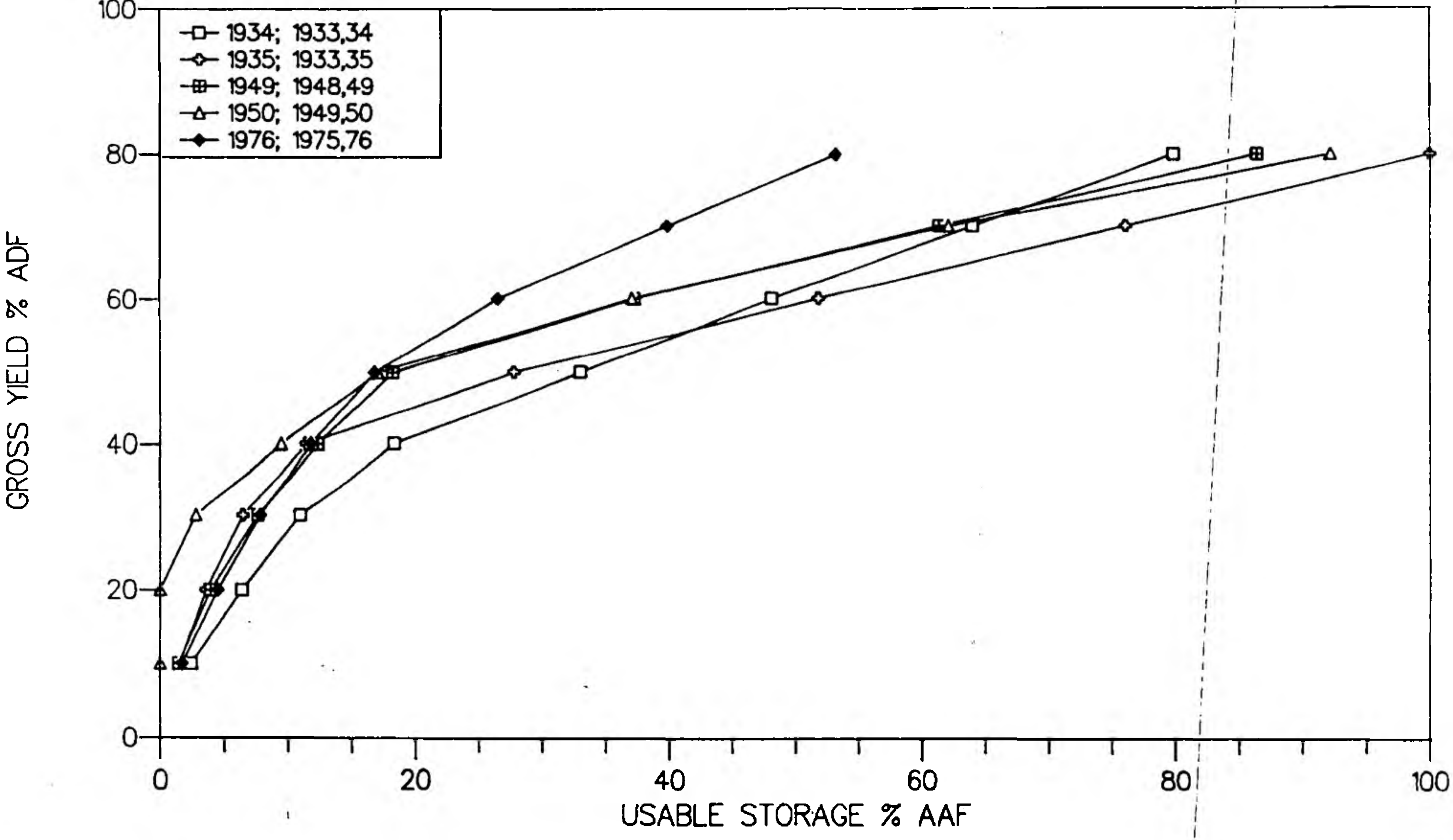


Figure 1.5 YIELD STORAGE RELATIONSHIPS FOR VYRNWY, STOCKS and ELY OUSE RECORDS

Based on behaviour analysis using monthly data.
uncorrected for end effects

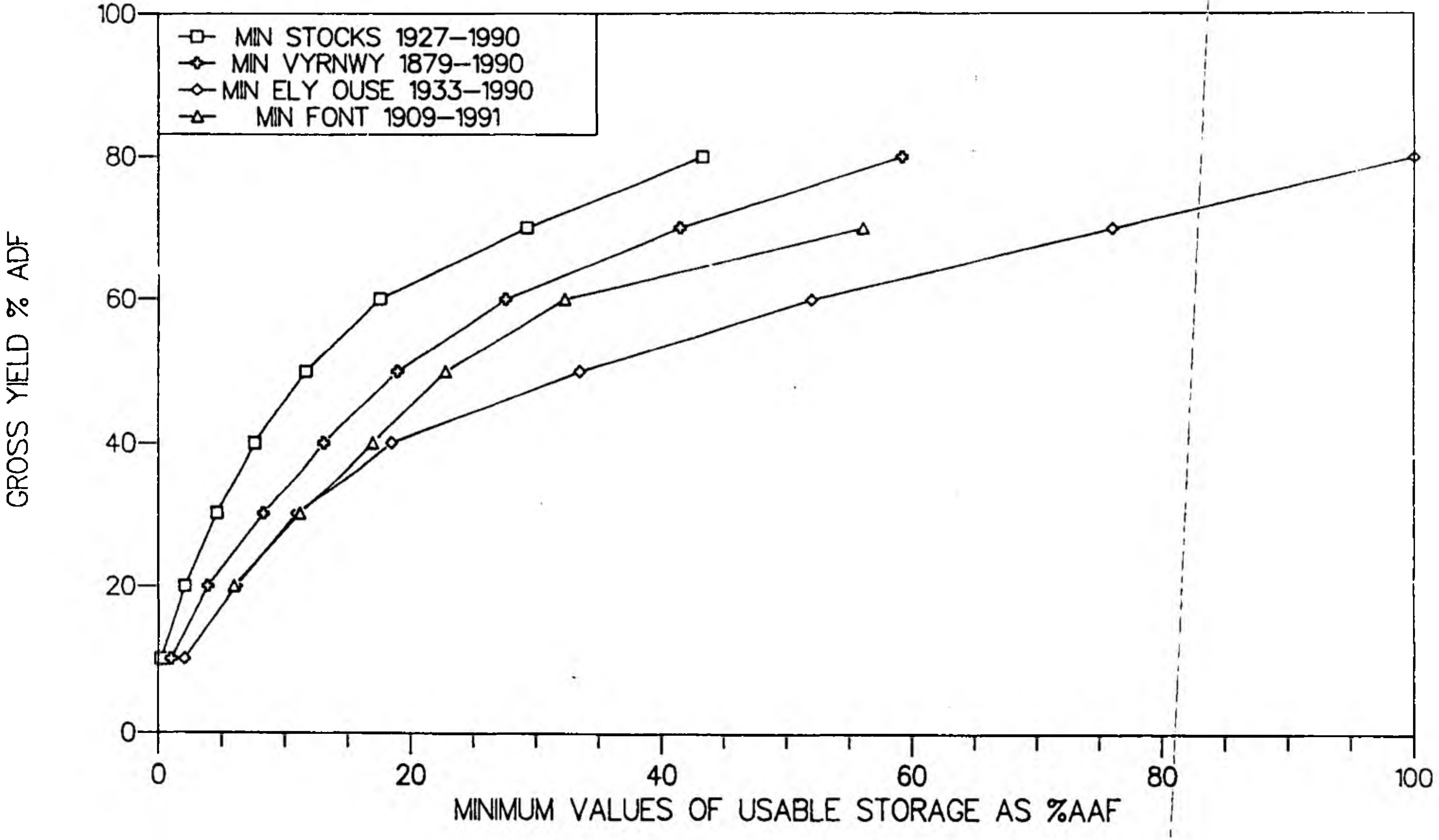


FIGURE 1.6 YIELD STORAGE RELATIONSHIPS
EXE RECONSTRUCTED RECORD 1856–1979
Based on behaviour analysis using monthly data.
uncorrected for end effects

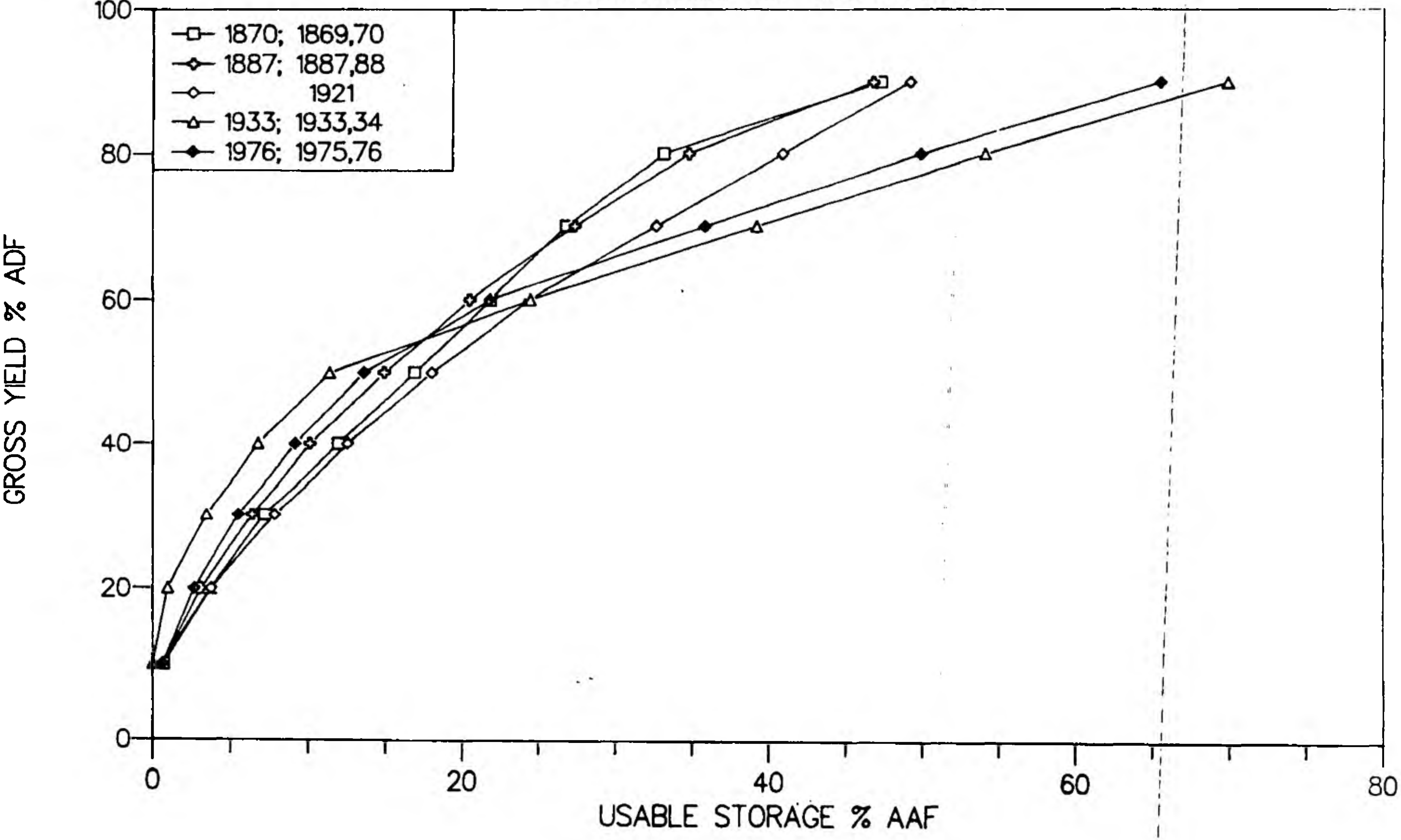


FIGURE 2.1 PERCENTAGE OF OCCASIONS FULL ON 1st APRIL VYRNWY, STOCKS and ELY OUSE RECORDS

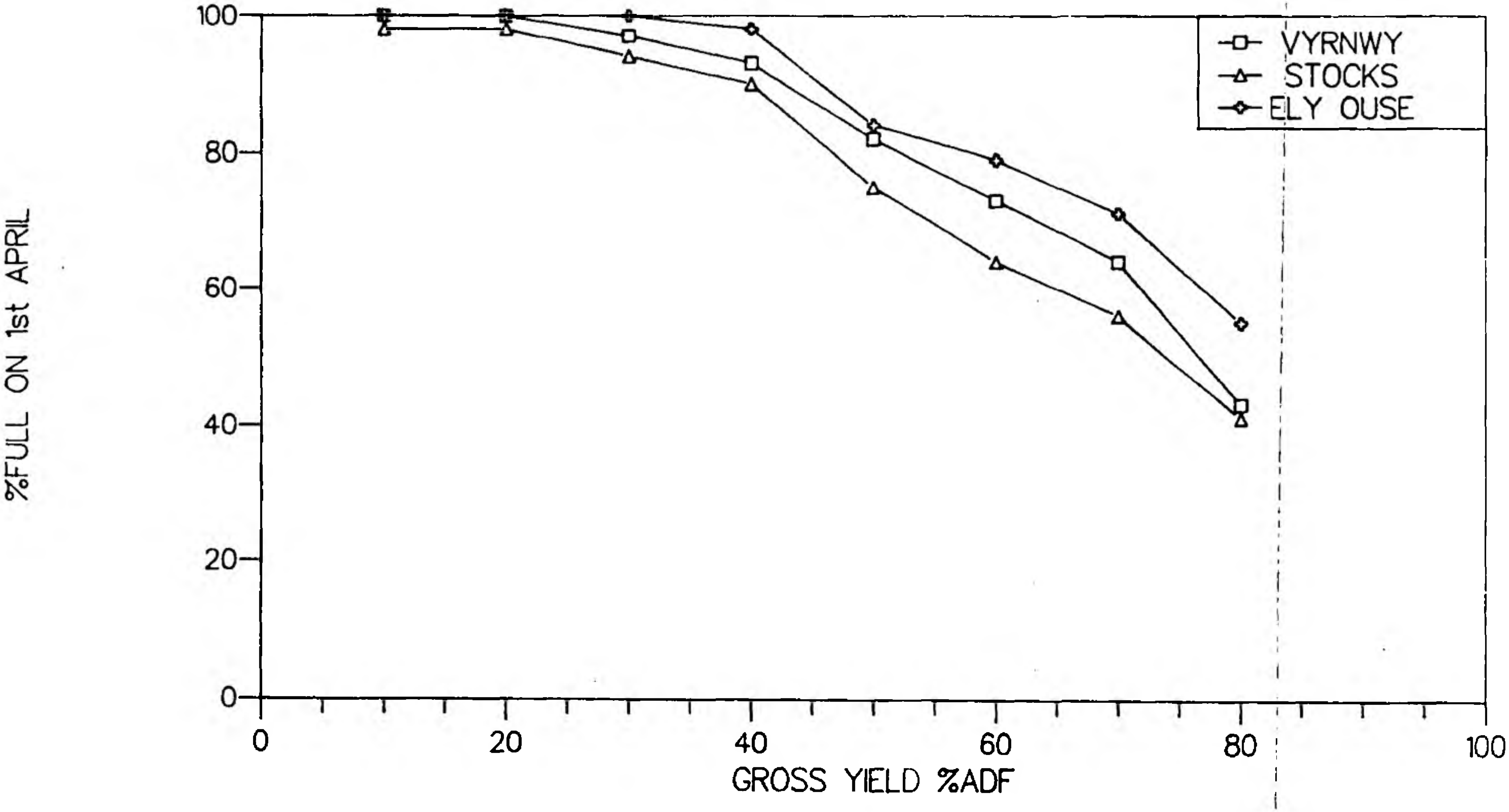


FIG 2.2 MAXIMUM DRAWDOWN AS A FUNCTION OF THE NUMBER OF DAYS STORAGE AT LEAST HISTORIC YIELD

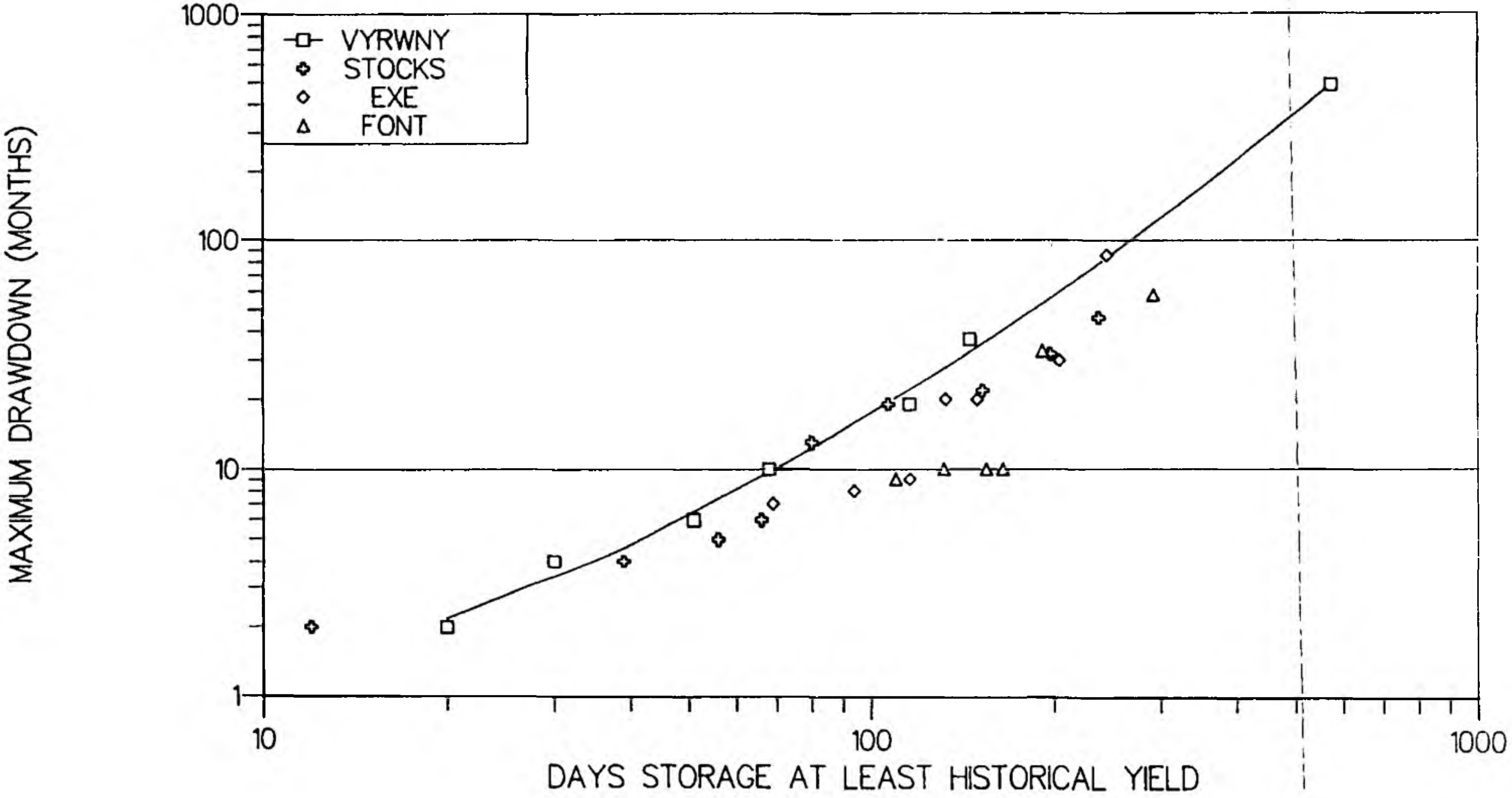


FIG 2.3 CRITICAL PERIOD AND MAXIMUM DRAWDOWN PERIOD vs STORAGE (DAYS)

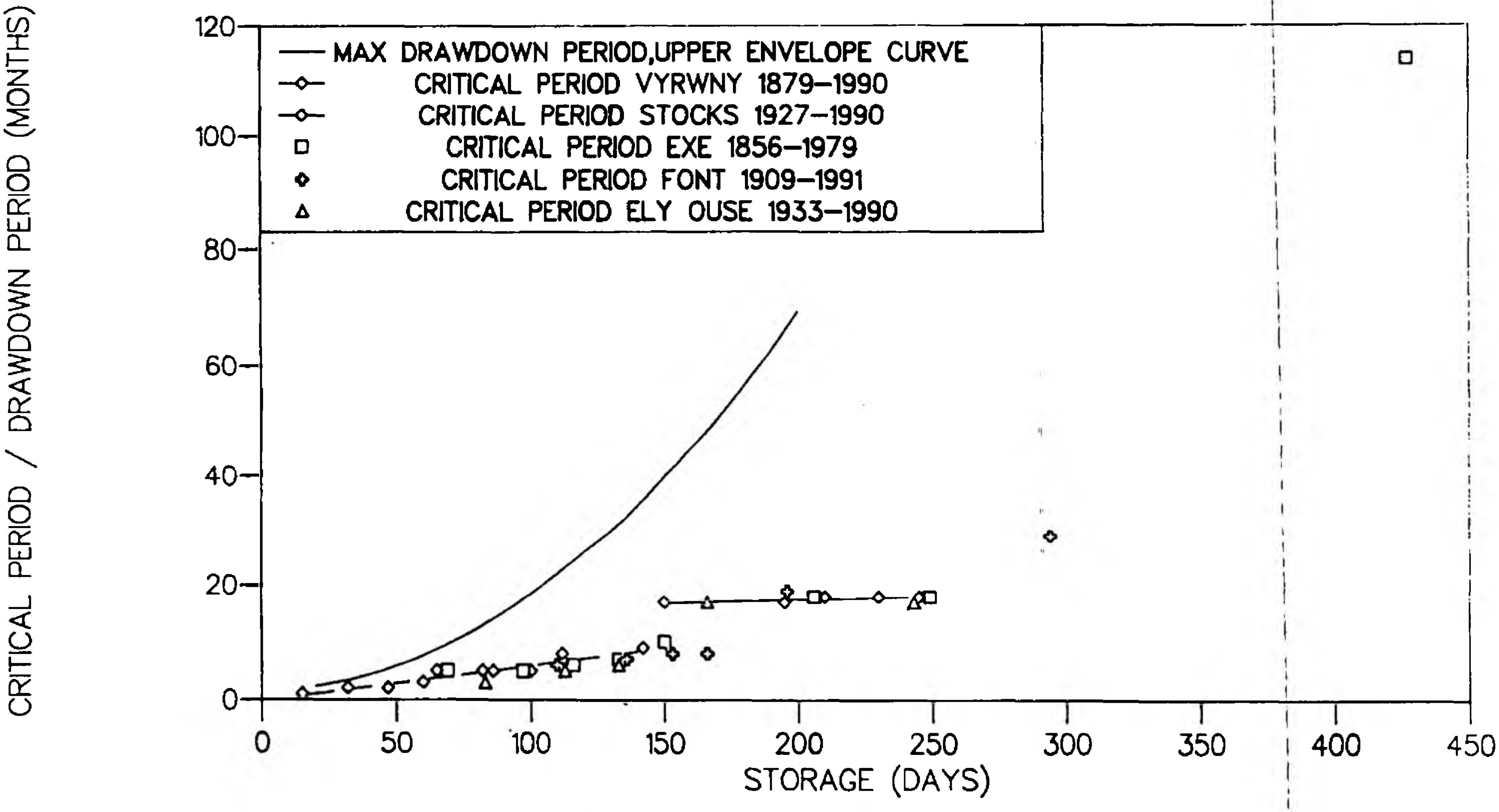
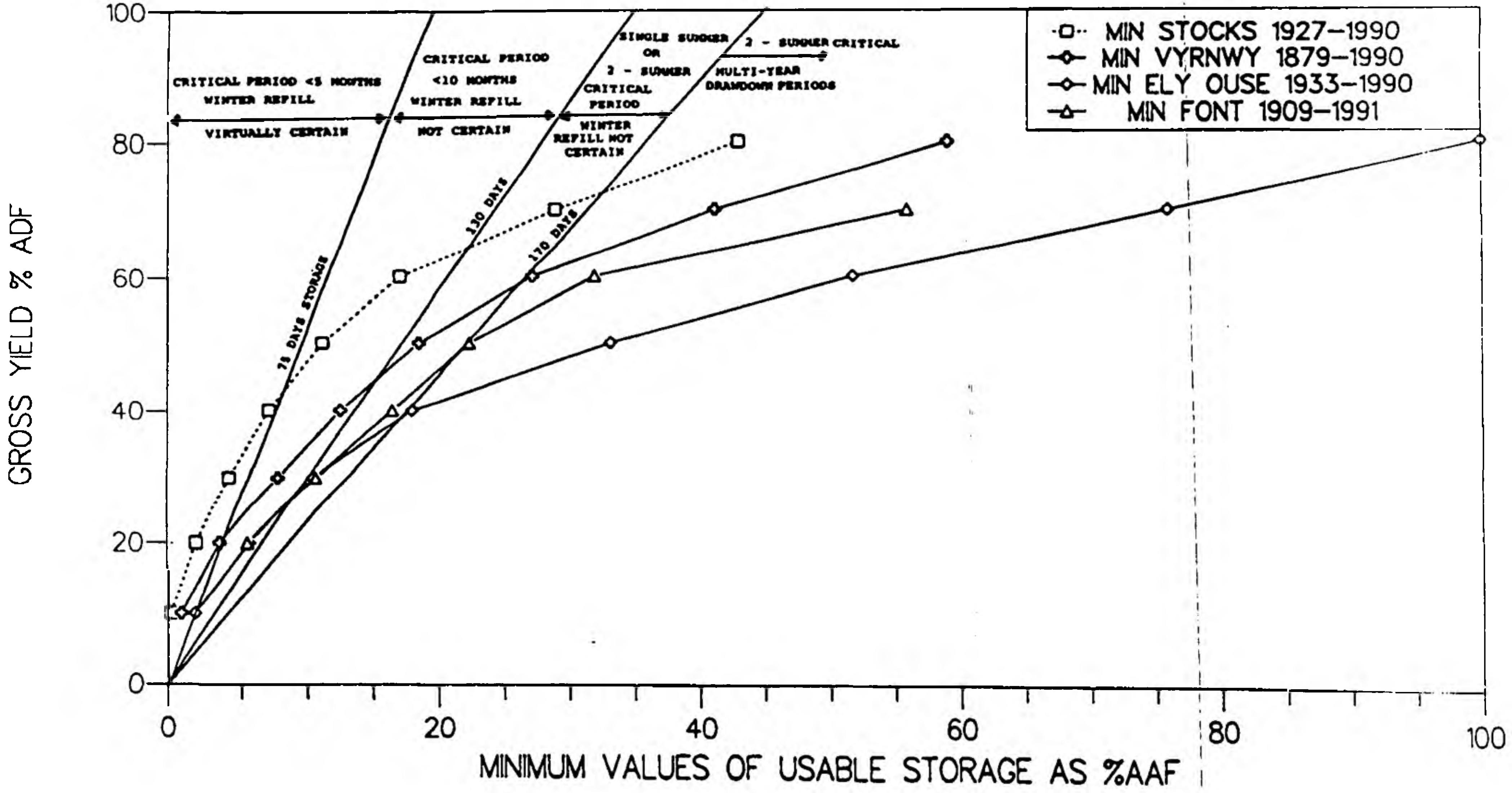


Figure 2.4 YIELD STORAGE RELATIONSHIPS WITH INDICATION OF CRITICAL PERIODS AND REFILL CONSIDERATIONS

Based on behaviour analysis using monthly data.
uncorrected for end effects



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APPENDIX 1: LIST OF SITES USED IN THE STUDY

Site Name	National Grid. Ref	Catchment Area (sq.km)	Period of Record (mm)	Average Runoff
Cray Reservoir	SN882215	10.9	1921-1976	1800
Elan at Caban Coch	SN934653	184	1908-1976	1260
Ely Ouse at Denver	TF588010	3430	1933-1990	146
Exe at Thorverton	SS936016	601	1856-1979	780
Stocks Reservoir	SD719546	37.0	1927-1990	1220
Taf Fechan	SO060117	33.8	1913-1983	1425
Vyrnwy	SJ019191	94.3	1879-1990	1440