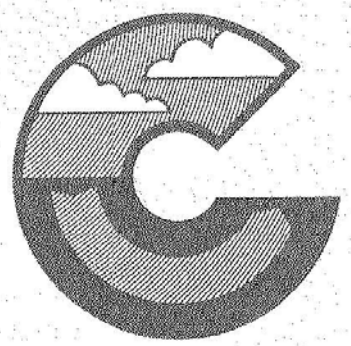


BRITISH HYDROLOGICAL SOCIETY

Palaeohydrology: context, components and application

BHS National Meeting
Institution of Civil Engineers
4th December 1995

Edited by Julia Branson

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Palaeohydrology:
Context, components and application

Julia Branson (ed.)

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Preface

This volume has been produced following the BHS National Meeting on palaeohydrology held on 4 December 1995 at the Institution of Civil Engineers. The meeting provided an introduction to the subject of palaeohydrology and the methods by which it is researched. The objectives of the BHS Millennium Project, which aims to build an archive of hydrological data spanning the last 2000 years, were also introduced.

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1

Definition and development of palaeohydrology

K J Gregory
Goldsmiths' College, University of London

Abstract

This paper examines the reasons for the development of palaeohydrology and its definition, outlines the purpose of palaeohydrology and summarises the progress made in palaeohydrological research. Some of the lessons learnt, and applications of the results of palaeohydrological investigations are also discussed.

1. REASONS FOR DEVELOPMENT AND DEFINITION

The basic need for palaeohydrology arose because there are many situations for which is required a longer sequence of hydrologic records than that available from the period of historical continuous records. Whereas many continuous hydrologic records relate, at the most, to the last 100 years, many records are much shorter. There is often a need to represent longer periods of time which include knowledge of extreme events possibly not represented in the recorded period where monitoring has been systematically undertaken on a continuous basis. To achieve such longer palaeohydrological records it is necessary to involve several disciplines; the techniques of a single discipline being insufficient, in themselves, to provide all the additional information that can be collected and coordinated. In the course of the involvement of other disciplines a quite distinctive approach has emerged which Baker (1991) has reminded us can be thought of as a 'think-back' process. Essentially this involves extrapolating knowledge of understanding of processes in the present back in time. Although palaeohydrology research has been developed comparatively recently and focused largely on recent time periods of hundreds or thousands of years and on the earth's surface, the techniques involved have also been applied to geological periods (Schumm, 1968) and also to other planets exemplified by the suggestions in relation to Mars (Baker, 1985). Palaeohydrology potentially furnishes an exciting approach because it involves several disciplines which provide information about hydrological events prior to periods of continuous hydrological records. However, there is a potential danger present in injudicious extrapolation referred to by Schumm (1977) and highlighted by Mark Twain as:

> 'In the space of one hundred and seventy-six years the Lower Mississippi has shortened itself two hundred and forty two miles. That is an average of a trifle

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> over one mile and a third per year. Therefore, any calm person, who is not blind or idiotic, can see in the Old Oolitic Silurian Period, just a million years ago next November, the Lower Mississippi River was upwards of one million three hundred thousand miles long, and stuck out over the Gulf of Mexico like a fishing rod. And by the same token any person can see that seven hundred and forty two years from now the Lower Mississippi will be only a mile and three quarters long'
>
> - Mark Twain, *Life on the Mississippi*, 1884.

It is necessary to have a definition of palaeohydrology which is comparable with those for palaeoclimatology and similar disciplines. Schumm (1965) produced the first formal definition of palaeohydrology and this was modified slightly (Gregory, 1983) to become:

> 'The science of the waters of the earth, their composition, distribution and movement on ancient landscapes from the occurrence of the first rainfall to the beginning of continuous historic hydrologic records'.

2. THE PURPOSE OF PALAEOHYDROLOGY

As indicated above the major reason for the development of palaeohydrology was to improve knowledge about hydrological conditions in periods prior to the availability of continuous records. This has led to the investigation of areas and time periods which could not be investigated in any other way. A major purpose of palaeohydrology has been to provide information about events, conditions, and hydrological situations not previously recorded and analysed, therefore providing data about events prior to the occurrence of hydrological records or data for areas that do not posses hydrological records. In addition it can facilitate the extrapolation of records from one area to another. By collection of information from periods and areas for which data are not hitherto available it has then been possible to enhance understanding of the way in which changes take place over time. Particularly important has been the reconstruction of changes due to the influence of human activity. This applies to the impact of human activity on the hydrological cycle and on the water balance, on sediment yield and solute production, and also on river channel morphology and basin characteristics. A particular example is the way in which changes of vegetation relate to the hydrological cycle: a number of investigations have analysed the hydrological effect of changes in land use and vegetation over the drainage basin but it has not always been remembered, until recently, that the ecological characteristics of river channels and the vegetation patterns of their flood plains have changed significantly, due to human activity, so that these alterations need to be included in palaeohydrological investigations (e.g. Gregory and Davis, 1992). In pursuing the purposes of palaeohydrology it has been necessary to develop new techniques as well as refine existing ones: exciting progress has been made in a number of areas and the contribution by application of a range of techniques is illustrated in *Background to Palaeohydrology* (Gregory, 1983). A further purpose of palaeohydrology has been to make a contribution to the understanding of the impact of global change. Hitherto emphasis has frequently been placed upon global climatic models especially GCM's but global models are not always at the appropriate scale or resolution for the impact of changes of climate to be easily documented. Because major impacts of global climatic change are felt through the hydrological cycle palaeohydrology potentially has a very important contribution to make.

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3. PROGRESS MADE IN PALAEOHYDROLOGY

In the development of palaeohydrology it is possible to identify four broad stages. The first formal recognition of palaeohydrology was in a study of the alluvial chronology of valleys in Wyoming when Leopold and Miller (1954) recognised the need to invoke an understanding of hydrological processes in the past, to enable the interpretation of the sequence of valley development. Some similar studies followed in the next decade but a second stage was introduced in 1965 when S A Schumm proposed an approach to Quaternary palaeohydrology. In that approach (Schumm, 1965) simple global relationships between mean annual precipitation, mean annual temperature and mean annual runoff were presented and a series of deductions made as to how palaeohydrological changes may have taken place under different climatic scenarios, for example as a result of glaciation or deglaciation. This was an extremely important formulation developed from earlier work by Langbein and others (1949) and it provided a basic quantitative approach to palaeohydrology, which has subsequently been developed by a number of authors and most recently is amenable to refinement using water balance models. Also at this time studies were undertaken of river channel changes which demonstrated that substantial adjustments of river channels in various parts of the world had occurred over recent centuries and certainly over the period since deglaciation following the last major period of glaciation. Important contributions in this regard were made by studies of underfit streams (Dury, 1964, 1965) and by studies of river metamorphosis by Schumm (1969, 1971), the latter following the approach initially indicated by the hydraulic engineer E W Lane (1955).

A third stage of development of palaeohydrology took place between 1977 and 1988 during research by an International Geological Correlation Programme Project 158 on the palaeohydrology of the temperate zone during the last 15,000 years. The project was organised in terms of two sub projects, one concerned with fluvial investigations and the other with investigations based upon lakes and mires; it provided the opportunity to co-ordinate research undertaken in several countries of the temperate zone and also fostered research, not only in individual basins but also by coordinating results from one area to another (Starkel, Gregory and Thornes, 1991). A fourth stage of development occurred when the International Association for Quaternary Research (INQUA) established a commission to investigate global continental palaeohydrology. That commission (GLOCOPH) was established initially for the five year period from 1991-1996 but will now continue to at least the next INQUA congress in 1999. The commission is established to coordinate palaeohydrology research from all parts of the world; significant progress has already been made in identifying the major research achievements and the way in which further work will be undertaken (Gregory, Starkel and Baker, 1995).

In the course of these stages of development it has become very evident that it is necessary for palaeohydrology to employ a multidisciplinary approach, and research programmes have depended very much upon multidisciplinary endeavour. The major disciplines involved are:

meteorology and climatology
hydrology
hydrogeology
palaeoecology
dendrochronology

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archaeology
geomorphology
sedimentology

Contributions already made as a result of developments in different disciplines and the contribution from the stages of development of palaeohydrology are reflected in the publications achieved. After 1965 a significant number of research papers were published and many of these are reflected in the book published by Schumm (1977) entitled *The Fluvial System*. Arising from the IGCP project 158 in the period 1977-1988 were a series of publications including *Background to Palaeohydrology* (Gregory, 1983), *A Handbook of Holocene Palaeoecology and Palaeohydrology* (Berglund, 1986), as well as contributions from specific areas such as those collated for the basin of the River Severn (Gregory, Lewin and Thornes, 1987) and from the Vistula (Starkel, 1991). The final results from the international project were published in a volume which included results from 14 different major basins in the temperate zone during the last 15,000 years (Starkel, Gregory and Thornes, 1991). The first results from the INQUA commission on GLOCOPH, initiated in 1991, have now begun to appear: a volume summarising the background to research on global continental palaeohydrology has been published (Gregory, Starkel and Baker, 1995) and the first research results presented at an international meeting in 1994 was published in early 1996 (Branson, Brown and Gregory, in 1996).

A further way of illustrating progress made in palaeohydrology is to outline the contributions made by particular disciplines; several of these are represented in the subsequent papers of this volume. Geomorphological contributions have been achieved in three major ways. First there have been many research results obtained by the calculation of former discharges for periods and areas for which no records are otherwise available; this is important particularly for the retrodiction of flood discharges. This approach has been assisted by the use of particular types of equations to estimate former events: Williams (1984) summarised the equations available. A special case is the development of palaeostage indicators (PSI) to facilitate the reconstruction of flood frequency for a number of areas; this has shown how flood frequency curves developed in this way can differ quite significantly from flood frequency curves developed by other methods (Baker, 1987). A second group of contributions has been made by studies of river channel changes; very important developments have been achieved in this area for particular countries, such as the changes along the Gila River in Arizona (Graf, 1988) and studies of the Vistula in Poland (Starkel, 1991). However, in addition, summary volumes (e.g. Petts, Moller and Roux, 1989) have exemplified the range of types of study that can be achieved. A third group of contributions has been associated with alluvial chronology, involving the use of simple general models such as those produced by Strahler (1956) and Wolman (1967) and has also derived from investigations in particular areas. In the UK there have been studies of regional and country-wide Holocene alluviation in river basins: using information from 59 published sites, Macklin and Lewin (1993) showed that eight major phases of alluviation could be identified and that there was widespread synchrony of Holocene fluvial episodes in Europe and the USA particularly over the last 5,000 years. In addition to these rather specific geomorphological contributions there have also been contributions achieved by the co-ordination of results over specific basins and arising from IGCP project 158 studies including the Severn basin (Gregory, Lewin and Thornes, 1987) where there was an attempt (Gregory and Lewin, 1987) to demonstrate all the interrelationships between changes that had taken place in the last 15,000 years.

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4. LEARNING FROM THE RESULTS OF PALAEOHYDROLOGICAL RESEARCH

From the research achieved so far it is clear that a number of conclusions can now be drawn; a number of significant contributions have been made and include:

- the possibility of providing data on events for periods and locations which do not have continuous hydrological records.
- the construction of flood frequency curves more reliably than by extrapolation.
- the documentation of past sediment yield and of historic variations.
- the impact of global climatic change through understanding of palaeohydrological conditions.
- improved understanding of how drainage basin changes affect hydrological events.
- analysis of river channel changes and understanding of reasons for adjustments.
- appreciation of river channel morphology in the past as a basis for river channel restoration and design with nature approaches.

Sufficient progress has therefore been achieved to ensure that the Millennium Project can be undertaken, and will provide an important resource of value to the appreciation of the hydrology of the last two thousand years and a vital foundation for understanding the hydrology of the future.

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2

River flow and groundwater level records - the instrumented era

Terry Marsh
Institute of Hydrology

Abstract

The UK has a wealth of contemporary hydrological data but most river flow and groundwater level series extend back only to the 1960s. Formally archived hydrometric series covering 100 years or more are rare - but exert a powerful influence on our understanding of long term runoff and recharge variability. A substantial number of references to additional historical datasets can be found in the literature and important, but under-exploited, holdings are thought to exist in the annals of measuring authorities no longer extant and other bodies with water interests. A recently launched National Water Archive initiative aims to collate, archive and make available a number of such records to provide a fuller understanding of hydrological conditions in the nineteenth century. This knowledge will also help to establish benchmarks against which to compare the increasing number of reconstructed runoff and recharge series, based mostly on long term rainfall and temperature datasets, which offer an insight into hydrological variability in the 17th and 18th centuries. Initial analyses of newly collated hydrometric datasets suggests that the volatility in runoff and recharge rates over the last decade has few, if any, close precedents during the instrumented era. If recent extremes are to be rigorously examined in a more complete historical perspective, critical appraisals of the hydrometric quality of early flow and groundwater records together with an assessment of the likely impacts of artificial influences are essential. As with most environmental datasets, particularly those with a historical dimension, professional management is required both to provide long term security and to maximise the utility of the datasets.

1. INTRODUCTION

In global terms, the UK currently maintains relatively dense networks of flow measurement stations and observation boreholes - a necessary response to the country's geographical diversity. We are much less well blessed in terms of the length of hydrometric records - this is especially true of those which have been systematically archived to allow general access. For monitoring sites incorporated in the National River Flow Archive (NRFA), maintained by the Institute of Hydrology the average record length is less than 25 years (see Figure 1) and only a little greater for well and borehole records incorporated in the National Groundwater Level Archive (NGLA), maintained by the

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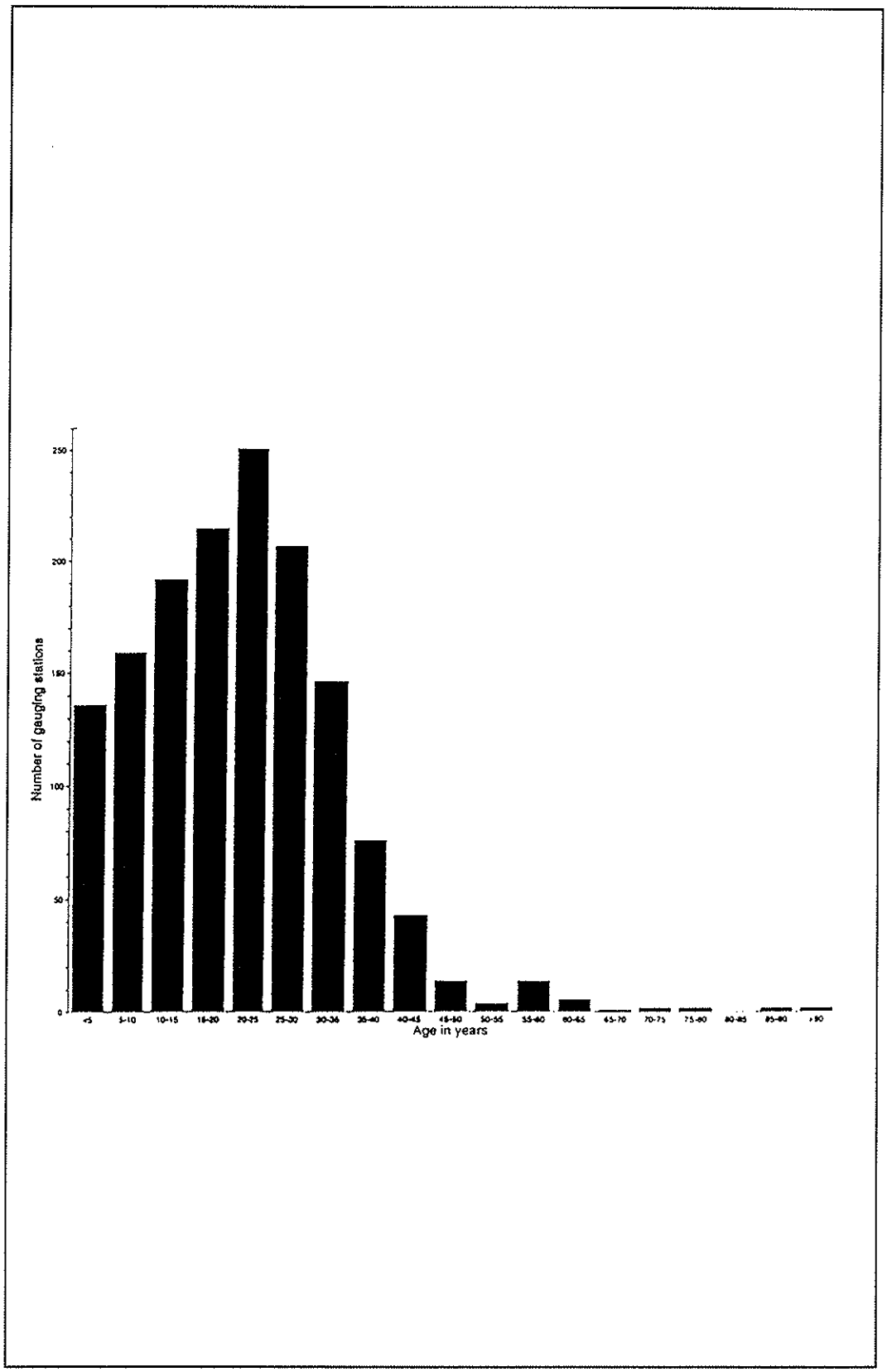


Figure 1 Distribution of record lengths for gauging stations in the National River Flow Archive

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British Geological Survey. The ability of most hydrometric datasets to characterise the full range of variability in rates of catchment runoff and aquifer recharge is thus necessarily compromised. This limitation assumes a particular importance at a time when the recent exceptional climatic conditions - with attendant interludes of flood and drought - have extended the recorded range of river flows and groundwater levels in a number of regions of the UK (Anon., 1995; Marsh *et al.* 1994). There is a broad consistency between the hydrological conditions experienced over the last decade or so and a number of favoured climate change scenarios (Rowntree *et al.*, 1993; Arnell and Reynard 1996). However, the inherent variability of the British climate dictates that any recent departures from the hydrological norm should be treated with caution and placed in as full a historical perspective as possible.

2. RIVER FLOW DATA

The phrase 'instrumented era' is somewhat ambiguous in the hydrometric context since an entire gauging station (or observation borehole) can legitimately be categorised as an instrument. Quantitative flow measurement may be considered to have begun with Hero's description of the volumetric method in the first century AD. Leonardo da Vinci made major contributions, unexploited at the time, to hydrometric knowledge (Levi, 1995) particularly in the understanding of velocity distribution. The seventeenth and eighteenth centuries saw much experimentation in the design of floats and the development of rotating vane current meters to assess river velocity. The latter began to be widely used over the second half of the nineteenth century in the UK. For example, a current meter designed by Joseph Saxton was used to assess the flow of the River Colne in 1834 as part of an examination of the water resources available to meet London's needs (Frazier, 1974). By the later years of the century, the development of hydraulic theory had advanced sufficiently for weirs to be used (and designed) for flow measurement purposes.

As the demand for river flow information grew the limitation of individual flow measurements or short term monitoring programmes became increasingly recognised. The need for sensibly continuous flow information, especially for water management purposes, stimulated the introduction of water level recorders and the necessity to routinely monitor stage-discharge relations. Captain W.N. McClean, working mainly in Scotland, laid the foundations for a modern integrated gauging station network (Werrity, 1987) but countrywide coverage awaited the Water Resources Act of 1963 and the availability of grant-aid for capital expenditure on gauging networks (Lees, 1987). The rapid network expansion encouraged by the Act is evident from Figure 2. Over the ensuing three decades the national network has grown to more than 1200 stations - embracing most measurement techniques.

The late 1960s represent a watershed in terms of river flow data; prior to that period there is a dearth of readily available data. Until recently, the Rivers Thames and Lee, and the Vyrnwy catchment, were alone on the NRFA in having records extending back to the nineteenth century. In 1993 the Institute of Hydrology, in collaboration with the regional

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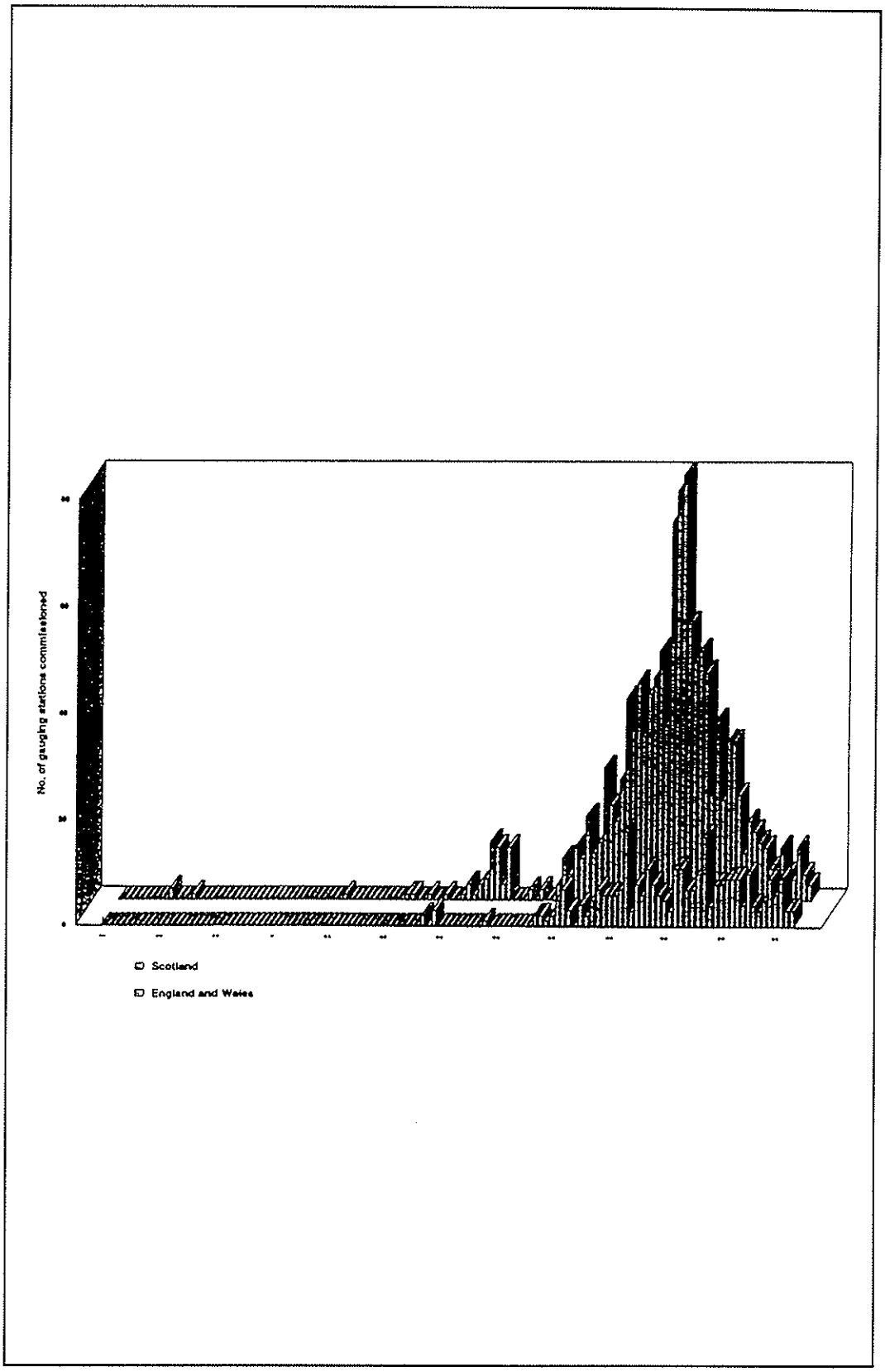


Figure 2 The growth of the United Kingdom gauging station network

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measuring authorities[1] instigated a programme to acquire a selection of long runoff records, most hitherto not formally held on national or regional archives. A number of such records have been referenced in the literature and some have been collated into regional collections. One compilation, now held by the Thames region of the Environment Agency, includes a very wide range of nineteenth century hydrological data. Such datasets provide a valuable opportunity to explore historical runoff variability and a few have the potential to examine hydrological conditions before 1800 on a quantitative basis.

An important milestone was passed in 1994 with the incorporation into the NRFA of a long monthly flow series for the Wendover Springs outflows. Flows are currently measured at a thin-plate weir which has been operated by British Waterways since the 1960s. The value of the contemporary data is greatly enhanced by the existence of an 1841-97 dataset (Anon., 1885) derived from a monthly count of lockages which fed water from the Wendover Arm to the, then, Grand Junction Canal; the possibility exists of extending the record back to 1793. The volumetric method is inherently accurate but lockage counts can introduce significant systematic errors into flow assessments. Nonetheless, the Wendover series (Figure 3) displays an encouraging general correlation with both the spring outflows at Sutton Poyntz (in the Chalk above Weymouth) and early discharge assessments for the Thames (Taylor 1876) over the 25 years from 1860. It also captures the main elements of runoff variability over the preceding 20 years, a period for which very few other directly measured flows are available. Unfortunately the Wendover Arm fell into disuse over the latter half of the nineteenth century and, being constructed largely in Chalk, began to leak badly around the 1880s. Eventually, after a period of substantial under-registration of runoff, the original monitoring site was abandoned.

Less direct measures of flow, especially lock levels (e.g. Crooks, 1994) and flood marks provide a means of indexing hydrological variability over a more extended timespan than continuous time series allow. Lock level data for the Thames and Severn stretch back to the first half of the nineteenth century and the Flood Studies Report (NERC, 1975) details events of an even earlier vintage - flooding at Shrewsbury being documented from 1672. Compilations of historical flood data appear in Rodda, Downing and Law (1976), Griffiths (1983), McEwan (1989), and Archer (1992). Extreme hydrological events may attract detailed examination (e.g. Acreman, 1989; Archer, 1993; Marsh *et al.*, 1994) and can provide a particularly interesting perspective on modern floods and droughts.

Increasingly, surrogate or reconstructed runoff series are shedding light on hydrological conditions over the last 200 years and beyond. Some, like the 130-year monthly sequence for Loch Leven (Sargent and Ledger, 1992) rely principally on the calibration of sluice records, others on catchment water balances. An interesting example, recently unearthed by Frank Law, details pumping rates from Deeping Fen (Glynn, 1836) providing a handle on runoff in the period 1830-35 and the severity of the 1834 drought. Rainfall data from the nearby Pode Hole raingauge - with records from 1726 - help place the Deeping Fen data in a longer term hydrological context.

[1] From April 1996 the Environment Agency in England and Wales and the Scottish Environmental Protection Agency; the Departments of Agriculture and Environment will continue a joint operation in Northern Ireland.

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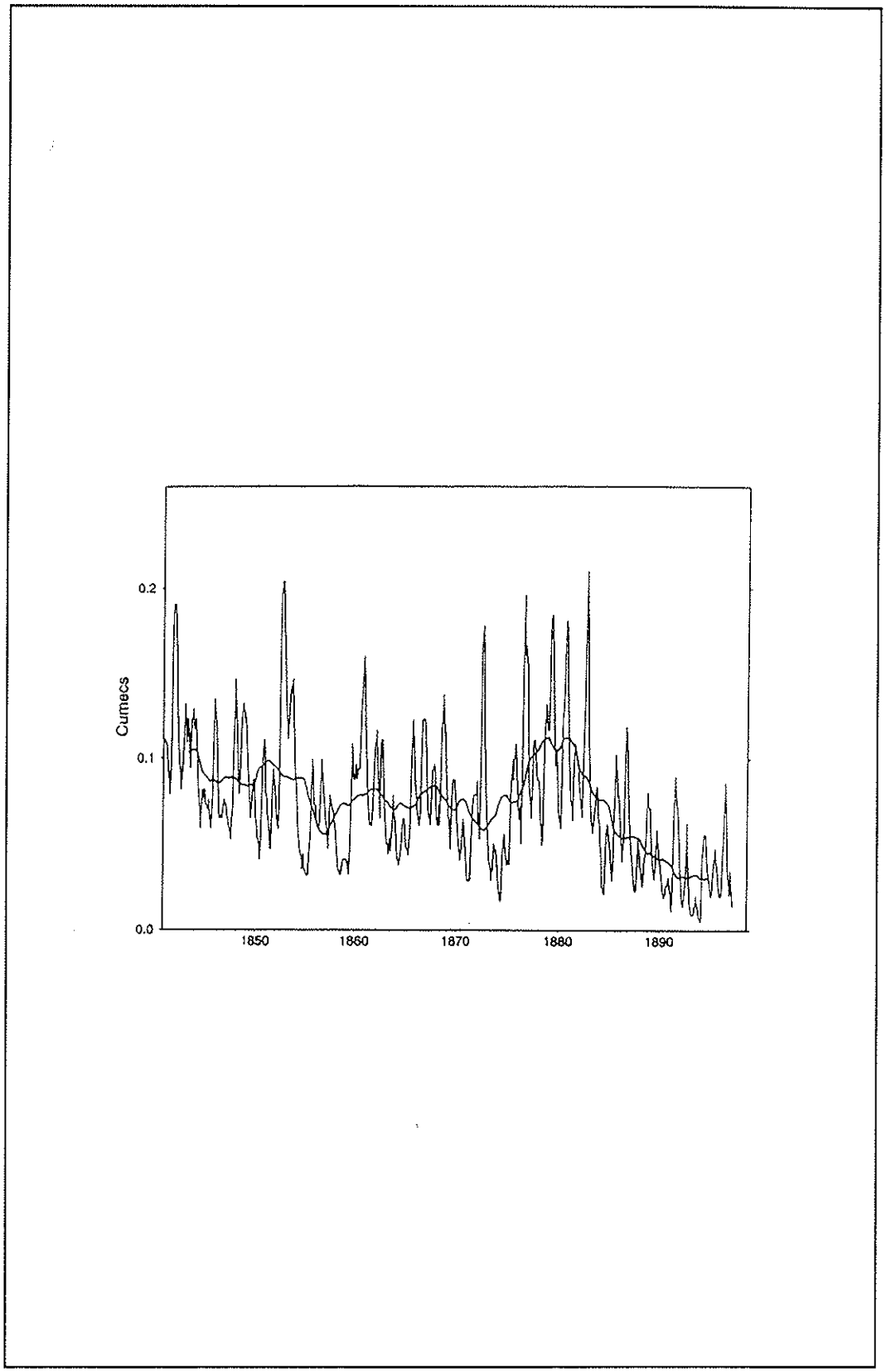


Figure 3 Wendover Springs runoff 1841-97

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Rainfall data series generally provide a much longer historical perspective than either river flow or groundwater level records - around 2000 raingauges were operational by 1880 - and are useful in hindcasting hydrometric series. River flow reconstructions based on a simple monthly rainfall runoff model (Wright, 1978) were published by the Climatic Research Unit (Jones *et al.*, 1984) for ten major catchments in England and Wales; most of the reconstructed series had start dates in the 1840-60 period but less reliable estimated flows (based on very skeletal raingauge networks) extend some series further back - in the case of Eynsham, on the Thames, to 1769. This publication includes very valuable tables of documentary historical information for the 10 catchments back to the middle of the sixteenth century; the authors stress the importance of a critical appraisal of source material before accepting its hydrological authenticity. A recent Environment Agency research commission (Jones and Lister, 1995) updated these reconstructed datasets and a second phase of the programme is extending the coverage to other key catchments in England and Wales.

For the Thames a reconstructed monthly series, based on the rainfall record for Kew, has been derived back to 1659 (Saxena *et al.* 1980). Such modelling exercises usefully extend our knowledge of historical runoff variability and the rarity of extreme events - under catchment and river conditions similar to those experienced over the calibration period (typically in the 1960-90 timeframe). Reservoir operation apart, the hydrological characteristics of many upland rivers have not been subject to the very substantial impact of changes in land use and river management practices which typify many English lowland rivers. Flow patterns in the River Thames for example have changed substantially over the last 100-150 years, limiting the degree to which reconstructed series can faithfully reflect historical flows.

2.1 Data Utility and Interpretation

Table 1 lists some recently acquired lengthy runoff records which have been incorporated in the NRFA. For many historical series the units of measurement may be uncertain and the recording interval unconventional or sporadic. In addition, the datasets are likely to be incomplete and of limited precision. Until further validation has been undertaken and details of the origin and method of derivation of the individual series are fully documented such datasets will be released on a restricted basis only. Considerable curatorial skill is normally necessary to establish the provenance of historical data, assess their hydrometric quality and prepare them for wide exploitation. Careful documentation, quality control and access to relevant spatial and reference material is essential if misinterpretation of the raw data is to be avoided. Potter (1978) provides a comprehensive guide to potentially valuable source material especially in relation to historical floods information (with numerous references) and outlines many of the pitfalls awaiting the unwary. The costs associated with locating, documenting and appraising long hydrometric records, which can easily exceed £20K for a lengthy series, continues to constitute a major disincentive to the systematic archiving of historical data.

When examining long hydrometric series it is important to recognise that major improvements in instrumentation and measuring techniques have taken place over the last 200 years. Equally, it is necessary to acknowledge that the impact of artificial disturbances on flow regimes has become ever more pervasive. This is of particular significance in the UK due to very modest flows which typify most rivers. Although mill

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Table 1 Long runoff series recently incorporated in the National River Flow Archive

Site	NRFA	NGR	Catchment Area	Period of Record	Measuring Authority	Comments
Loch Leven	17806	NT171993	158.3	1855-1993	Loch Leven Trustees	Derived loch inflows (monthly)
Wendover Springs	39801	SP869083	9.5	1841-97	British Waterways	Based on Tringford lockage count (monthly)
Sutton Poyntz Spr.	44814	SY707844	11.3	1858-1970	Wessex Water Plc	'Spot' monthly flows, significant gaps.
Bedhampton Spr.	42812	SU712862	93.0	1908-1992	Newcastle and Gateshead Waterworks Co.	Derived monthly flows
Tyne Reservoir Gr	23820	NY960760	96.2	1904-1957		Monthly yields for a group of reservoirs
Trib.of Endon Bk (Deep Hayes Res.)	28805	SJ961534	9.8	1915-1964	South Staffordshire Water Board	Naturalised monthly flows

operations, in particular, could affect low flow regimes in Victorian times, the net effect of abstractions and discharges was generally minor; today the complex patterns of water utilisation have a profound impact on the natural regimes of many rivers. This underlines the need for critical reviews of long river records to ensure that they can be properly exploited and allow temporal hydrological comparisons to be fairly undertaken.

The need for such appraisals is not confined to little-used or recently acquired series. The long naturalised flow series for the River Thames at Kingston - one of the most heavily used runoff records in the world - incorporates daily adjustments to account for the major upstream abstractions for London's water supply. These have increased by an order of magnitude over the last 120 years but hydrometric imprecision has probably had a greater effect on the dataset's utility. Teddington Weir, which served as the gauging station until the commissioning of the ultrasonic station at Kingston, underwent many structural changes over the hundred years following its major refurbishment in 1883. It was designed principally to retain levels for navigation purposes and had clear limitations for measuring discharge, especially in the extreme flows ranges (see Plates 1 and 2). A recent rainfall-runoff modelling exercise strongly suggests that the suspected underestimation of historical low flows, largely attributable to leakage through the Teddington Weir complex (Mander, 1978), is of a greater magnitude than previously thought (Littlewood and Marsh, 1996). Once the conventional adjustments for such losses are increased to a more realistic level, the severity of recent drought episodes (especially those of 1976 and 1989-92) relative to historical droughts increases significantly.

Despite the shortcomings of many early series, most of which are to be expected with hydrometric series of long vintage, preliminary analyses have revealed an interesting measure of spatial coherence regarding a number of early very dry or very wet episodes for example, in the early 1850s and 1880s. At other times regional variations in hydrological conditions have been considerable although not, on current evidence, as

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Plate 1 *Teddington Weir during the flood of November 1894.* *(Photo: Environment Agency, Thames Region)*

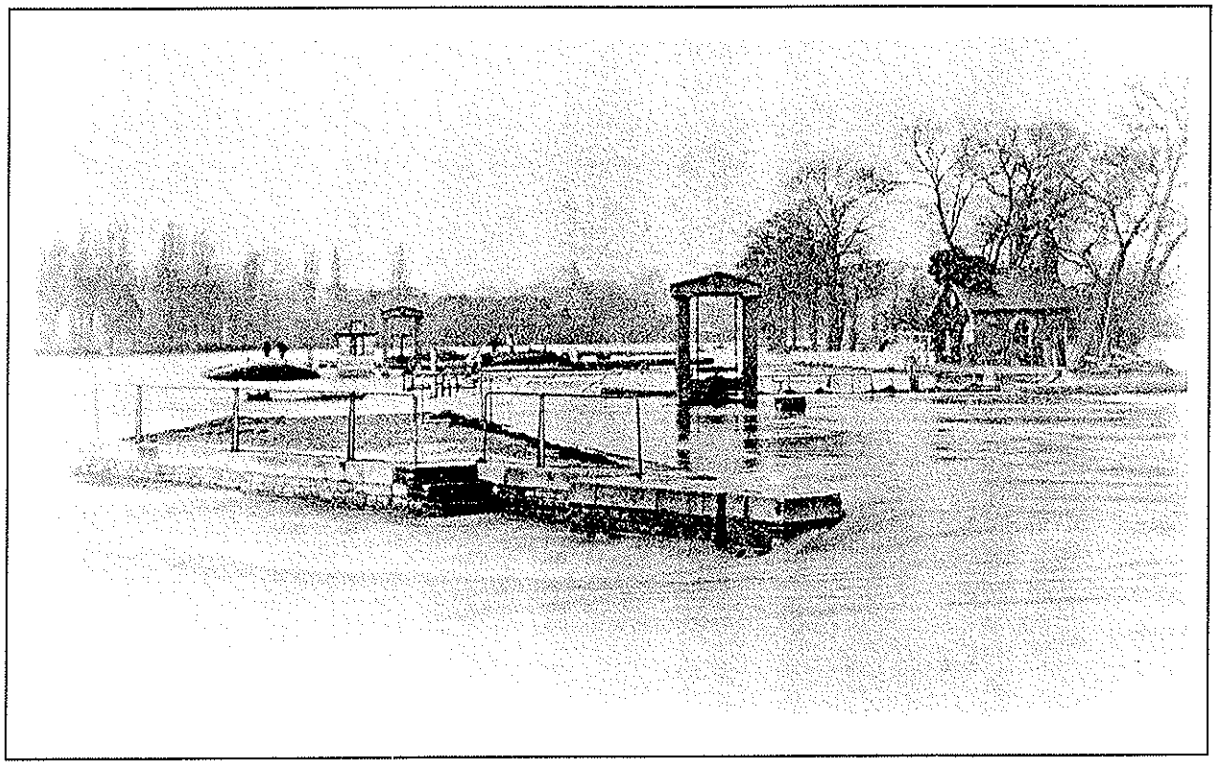
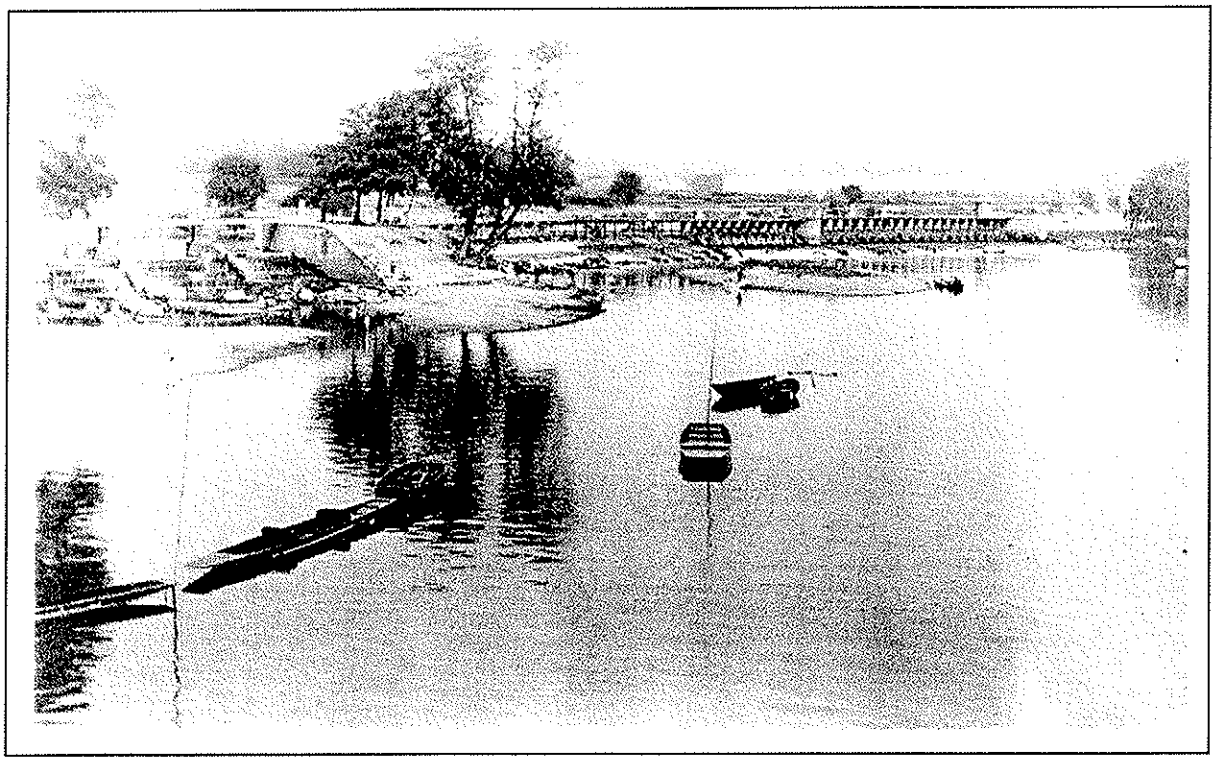


Plate 2 *Downstream of Teddington weir during the 1921 drought.* *(Photo: Environment Agency, Thames Region)*



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notable as those recently experienced. The running mean trace for the Bedhampton Springs outflows (Figure 4) illustrates the influence that extreme hydrological conditions early and late in the record can exert on the perception of any overall trend. Generally, in the time frame of the last 200 years, UK runoff series display significant perturbations but about a relatively stable mean.

3. OBSERVATION BOREHOLES

By its nature groundwater rarely attracts public or political attention with the same immediacy as river systems. Nonetheless, groundwater has been the subject of scientific curiosity for thousands of years and sustained many communities over a similar timespan. Groundwater is the major source of public supplies in much of eastern and southern England and is locally important in the more impermeable west and north. The widespread use of wells, especially following the pollution of river systems during and following the Industrial Revolution, has provided a legacy of thousands of potential measurement sites affording plenty of scope for opportunistic groundwater level monitoring.

Notwithstanding this favourable backcloth - and the relatively modest costs of maintaining and operating groundwater networks - nationally archived long records are rare and those that do exist are largely confined to the Chalk. This is despite the foundation of the Geological Society in 1807 and the Geological Survey in 1835. In the early nineteenth century information from wells and boreholes were seen as being valuable principally to establish the local stratigraphy. The pioneering work of the Rev. J.C. Clutterbuck (1850), who highlighted the progressive decline in levels in the confined Chalk aquifer below London, demonstrated the value of systematic monitoring in relation to water resources. This early recognition of the importance of groundwater level measurements failed to trigger any nationally coordinated monitoring programme. It was not until the 1950s that the Geological Survey began to measure and collate groundwater level data from the major aquifers. As with flow measurement, a marked acceleration in monitoring awaited the imposition of statutory duties (to assess resources and license abstractions) by the 1963 Water Act.

Of the 5000 wells and boreholes in the current Environment Agency monitoring network only around a dozen have level records commencing before 1900 (McKenzie *et al.*, 1995). The National Groundwater Level Archive - which comprises around 170 representative boreholes (although historical data for an additional 3000 sites are also stored) - includes only four datasets, all relating to the Chalk, extending beyond 100 years. Wallcharts have been published illustrating the long term water level variations for two of these: Chilgrove in West Sussex and Dalton Holme in the Yorkshire Wolds; it is hoped to issue a third, for Therfield Rectory (Hertfordshire) in the near future. Taken together these notable groundwater level series provide an aquifer-wide appreciation of recharge variability back into the late-Victorian era. Other less complete datasets, usefully augmented by the long term monitoring of spring outflows, allow a quantitative understanding of water-level behaviour over a period of almost 200 years - the oldest known multi-year sequence of groundwater levels is for the Chalk at Detley, near Maidstone in Kent, covering 1819-32 (Bland, 1832) and a few useful compilations of annual levels in the nineteenth century have been published (e.g. Anon., 1885).

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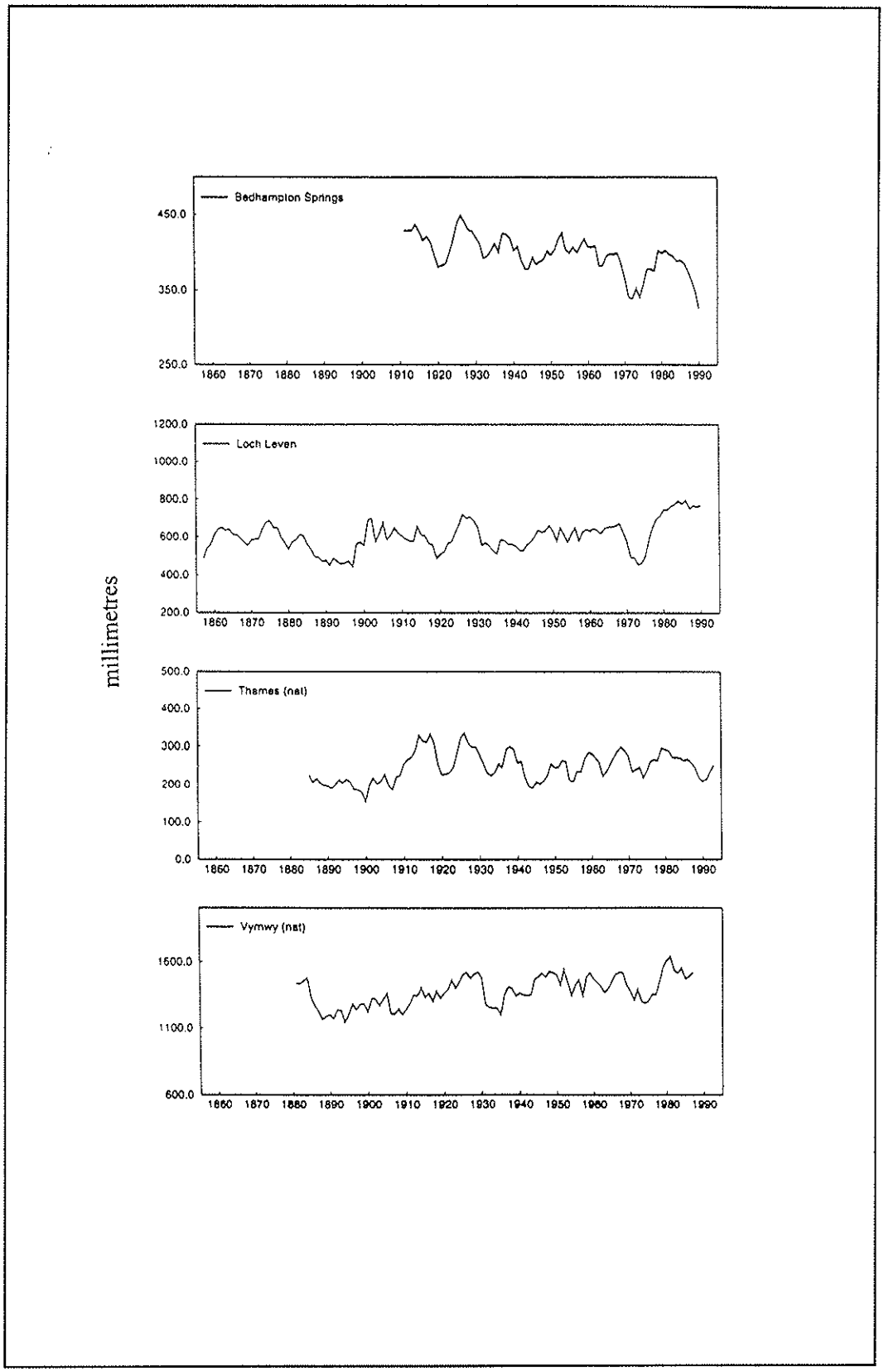
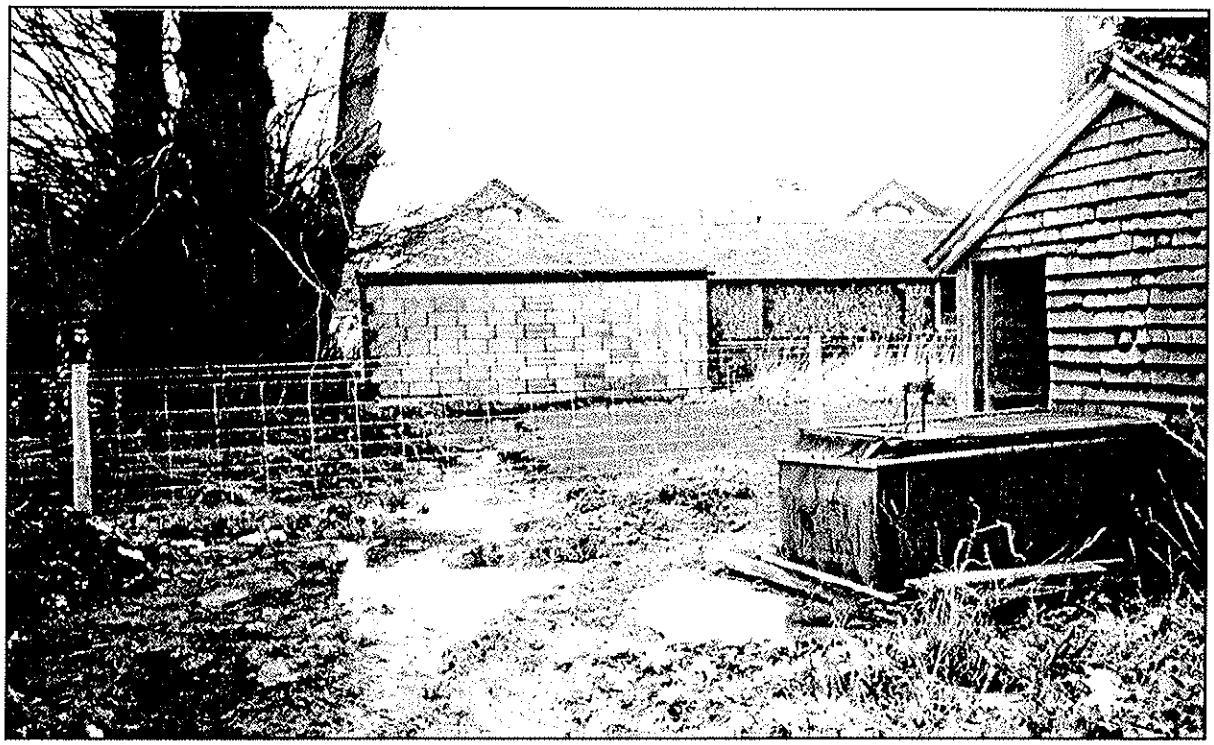


Figure 4 Long term runoff series for Great Britain

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Plate 3 Chilgrove House borehole overflowing in January 1994. *(Photo: Philip Turton)*



Those long groundwater level records which have been collated are of immense and unique value and have largely fashioned our understanding of long term recharge variability. The Chilgrove dataset (Thomson, 1938; British Geological Survey; 1990) is especially noteworthy: groundwater level recording began in 1836 and the series is thought to be the longest sensibly continuous groundwater level record in the world. The large seasonal range, around 40 metres together with the very minor impact of abstractions (a disturbing influence at many sites) make the Chilgrove well particularly suited to resource monitoring. However, exceptional rainfall over the 1993/94 winter produced artesian conditions which brought severe and prolonged flooding to Chichester, and demonstrated the limitations of the site under extreme conditions (see Plate 3). This ceiling to the recordable range underscores the importance of contemporary reports in building on the utility of the basic water level information. Records gleaned from West Sussex Archives (Hills, 1872) refer to eight occasions of flooding in Chichester over the period 1763-1866, most doubtless exacerbated by exceptional groundwater levels. Initial analyses suggest that during the post-1836 era, only in 1852 has the borehole overflowed for a comparable period to that of early 1994.

3.1 Quality Assurance

Although inherently more straightforward than river flow measurement, groundwater level monitoring is still attended by appreciable hydrometric uncertainty and artificial influences on the water-table can be substantial. Both effects may vary greatly through time. The lengthy groundwater level record for the Therfield Rectory well provides a unique insight into recharge variations in an area where annual average rainfall and potential evaporation losses are comparable. It also constitutes a telling illustration of the measurement problems that can be encountered. Routine level measurement began at Therfield in 1883

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after the Reverend Hale noticed a correlation between winter rainfall and the recovery of the water-table. The well is deep - over 80 metres - and the depth to the water-table was determined using a simple weighted line. Unfortunately, the lines used were ill-suited to the task: one, first used in 1903, was checked in 1921 and found to have stretched 6.93 metres; the replacement line is reported to have shrunk considerably over the ensuing decade. Obviously the linear corrections later applied cannot be expected to fully correct these systematic errors and represent actual groundwater level changes.

The frequency with which water levels are logged can also be important when interpreting water-table variability. A few boreholes now furnish a near continuous telemetered record of levels and electronic data loggers are increasing replacing chart recorders which have been widely employed over the last 50 years. Historically, monthly or intermittent measurements were more typical. Although groundwater level variations are relatively muted and reasonably predictable, early monitoring regimes often failed to capture the full groundwater level range. As a consequence, a critical review of the data is essential when comparing contemporary and early data series.

Most observation wells and boreholes are sited to avoid the worst effects of local groundwater pumping. In some areas however, the impact of abstractions is substantial. The cessation of minewater pumping, which accompanied the decline of the coal industry in the North-East, has led to an increase in water levels in parts of the Magnesian Limestone. A more historically significant example is provided by the behaviour of levels in the Trafalgar Square borehole which penetrates the confined Chalk aquifer. Groundwater abstraction triggered a significant lowering of the water-table from early in the nineteenth century and groundwater levels declined by around 70 metres up to the Second World War (Water Resources Board, 1972). Subsequently, abstraction rates decreased as industrial demand declined and many users switched to piped supplies from reservoirs in the Thames Valley. Water levels stabilised and, from the mid-1960s, began to rise (see Figure 5). Such trends are sensibly independent of climatic variations and misinterpretation may easily occur if appropriate descriptive and reference information is not systematically stored alongside the individual time series, this is especially true of aquifer units affected by short term or seasonal abstractions.

Where human influence is limited, long term groundwater level records - like those for runoff -exhibit no overall trend but sustained departures from the mean - see Figure 6. Substantial and protracted departures from the seasonal average have been a feature of the last decade which has witnessed water-table variations close to the extreme of the recorded range. The summer of 1992 saw overall groundwater resources as low as at any time this century (Marsh *et al.*, 1994) but the subsequent recovery produce near record winter peaks over the succeeding two winters (Anon, 1995). The interplay of unusual rainfall, evaporation and soil moisture conditions has produced exceptional spatial and temporal differences in recharge rates for which, on the limited long term evidence currently available, there is no close modern parallel.

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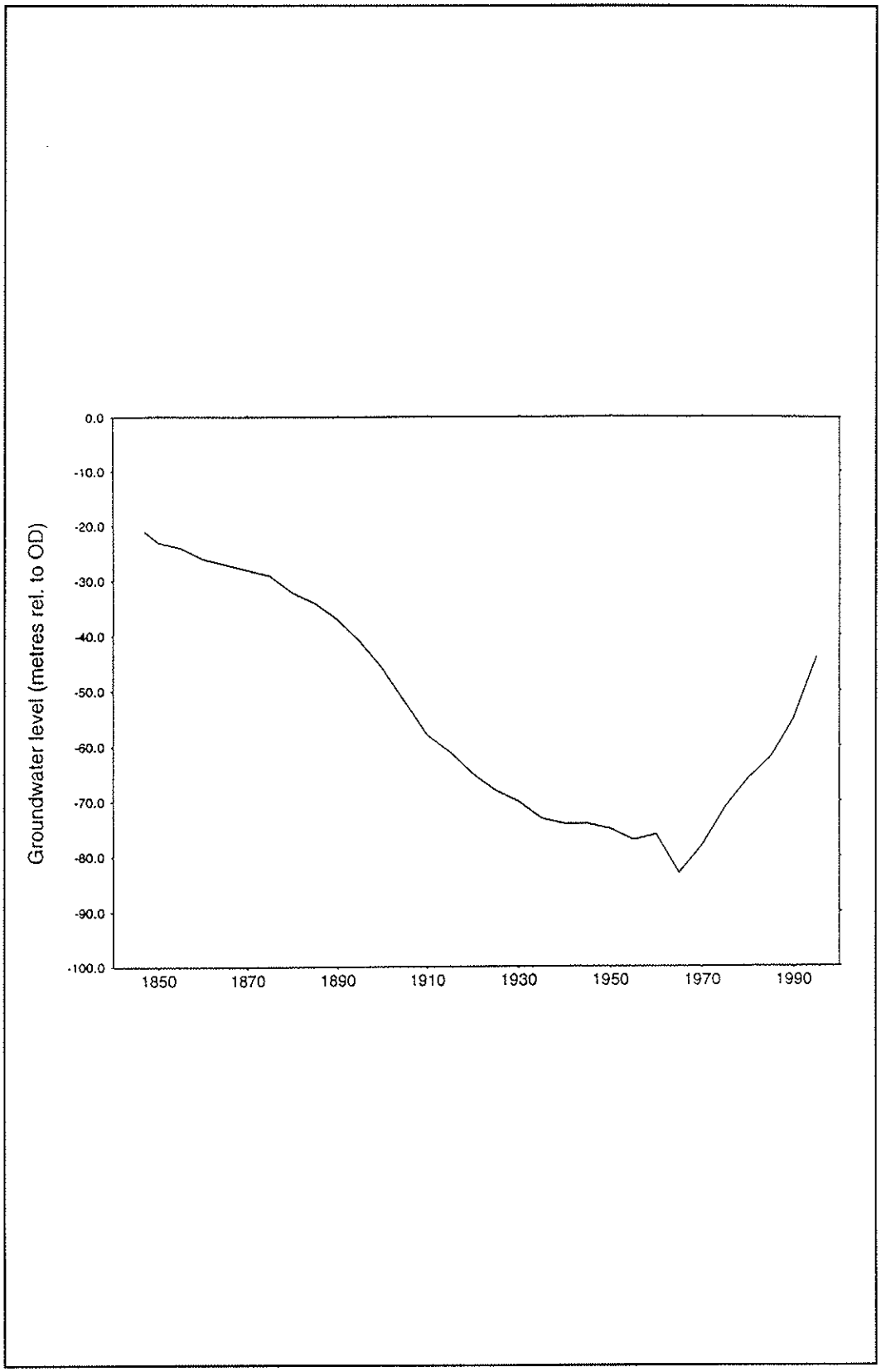


Figure 5 The decline and partial recovery of groundwater levels at Trafalgar Square (based on levels at 5-yearly intervals)

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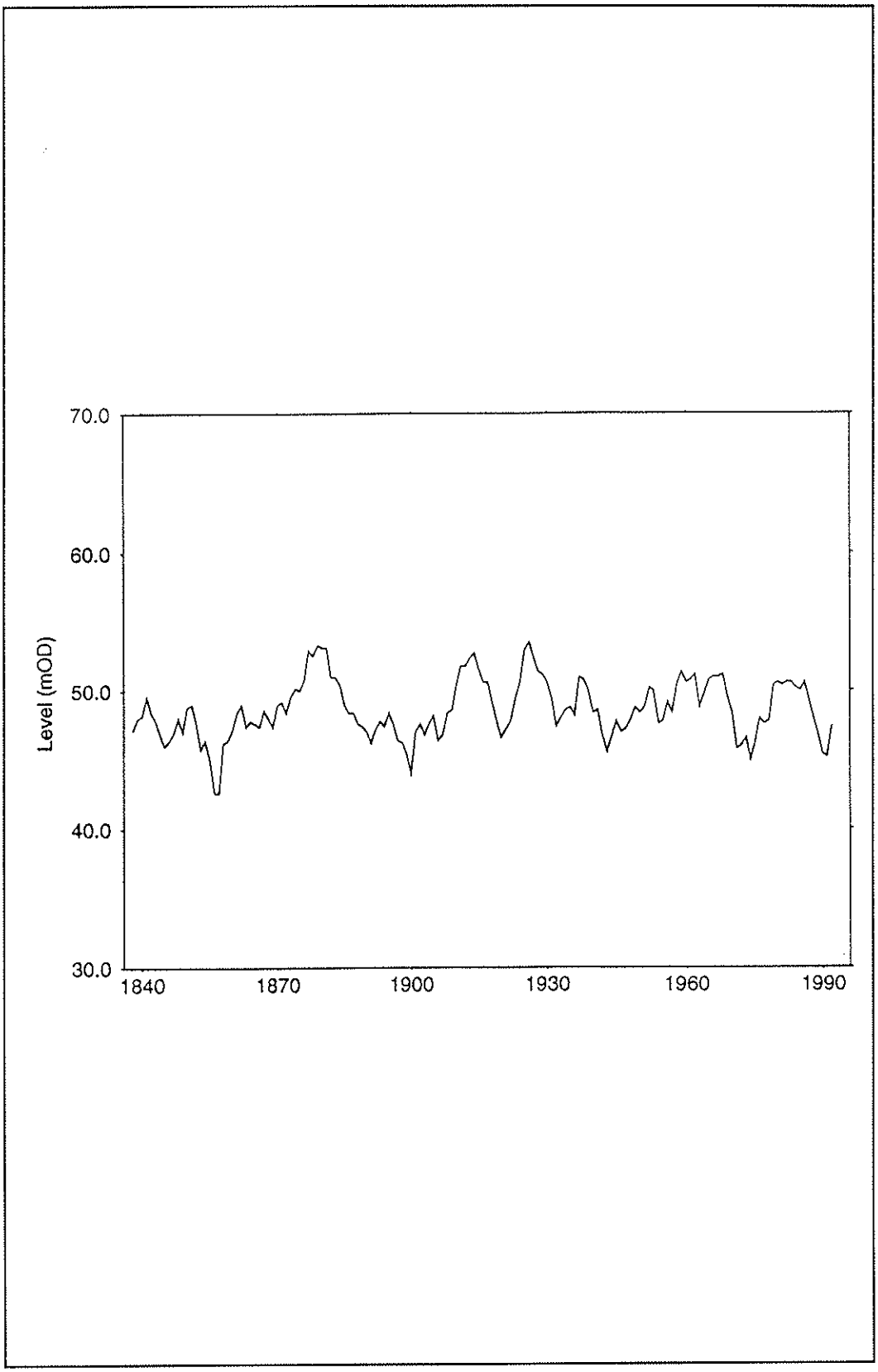


Figure 6 Average groundwater levels for the Chilgrove House well (5-year running mean)

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4. CONCLUSION

In a review of available UK discharge data in 1978, Potter observed that data are poor prior to the present century, rare in the last and practically non-existent before that. At the time, similar strictures could have been applied to readily available groundwater level data. Nearly 30 years on several factors have helped produce greater interest in long hydrometric records and encouraged moves towards a more professional stewardship of the UK's legacy of hydrological data. An increasing interest in palaeohydrology coincides with, and partly results from, a recognition that the lack of overall trend in rainfall, runoff and groundwater level records - which underpins water management in the UK, as elsewhere, may no longer form a reliable basis for the development of future policies and management strategies. This underlines the need to explore hydrological variability across a far broader timespan than hitherto, whilst attempting to assess how effectively fauna and flora adjusted to unusual conditions.

Intensive hydrometric monitoring programmes have yielded a wealth of hydrometric data over the last 30-40 years. Much more limited data, correctly interpreted, effectively characterise hydrological conditions over the last century or so. Carefully documented and validated earlier data are now helping to illuminate the more shadowy hydrological recesses of the nineteenth century and, exploiting correlations with rainfall and temperature data, provide a mechanism for quantifying - at least generally - conditions in the latter half of the 17th century. The diversity of UK river systems and aquifers, historical variations in hydrometric accuracy and the increasing importance of anthropogenic effects all underpin the need for significant resources to be devoted to ensuring that the current thrust towards increased data availability is accompanied by a corresponding increase in hydrological knowledge.

ACKNOWLEDGEMENTS

The help of Samantha Green and Felicity Sanderson (Institute of Hydrology) and Andrew McKenzie (BGS) in the preparation of this paper is gratefully acknowledged as is the continuing cooperation of the measuring authorities in helping to make available neglected hydrometric series. Particular thanks are due to Frank Law for his tireless detective work in locating valuable historical material.

Note: The National Water Archive's long record initiative is an ongoing project and further lengthy records, whether of springs, runoff, river levels, well levels or bourne flow occurrences, would be welcomed; holders of such data are invited to contact the Institute of Hydrology.

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3

Peatlands, palaeoclimates, palaeohydrology

F.M. Chambers
Centre for Environmental Change and Quaternary Research, Department of Geography and Geology, Cheltenham and Gloucester College of Higher Education

Abstract

Peatlands have been a major part of the landscape in Britain and Ireland for thousands of years. Their deposits accumulate sequentially, and they remain incompletely decayed; so, as they accumulate, bogs become a stratified repository of evidence for past environmental conditions, and can yield palaeohydrological data covering several millennia. Ombrotrophic (rain-fed) mires are particularly amenable to detailed palaeohydrological study, and have the potential to provide information about hydrological changes, on decadal or century timescales. Sub-fossil timbers, found in bogs, can be precisely dated and imply major hydrological changes in the prehistory of the British Isles. Examples of peat palaeohydrological studies are discussed and the implications of their data for contemporary hydrologists are briefly explored.

1. PEATLANDS

Peatlands can cover large tracts of land, and in places can be several metres thick. Taylor (1983) estimated that, by AD 1800, peatlands covered some 6% of the landscape of Britain and some 16% of Ireland. These figures greatly exceed the areas of large freshwater lakes and rivers in the British Isles. When one considers that some 80% (or more) of peat in temperate latitudes is comprised of water, one can begin to appreciate the hydrological significance of peatlands in the British Isles. Although human activity in Britain over the past two centuries has altered - even destroyed - many lowland peatlands, there remain large areas of upland peats in Scotland, northern England, Wales and south-west England. In Ireland there remain even more extensive peatlands, particularly in the west and over the Central Irish Plain.

Much of the remaining peatland in the British Isles supports bog (as opposed to fen). Bogs that apparently depend upon rainfall for their sustenance, both in terms of moisture and nutrients, are termed ombrotrophic; in the British Isles, there are two types: raised mires and blanket mires. Raised mires are typically dome-shaped, up to a few kilometres in diameter, 5-12 m in thickness, with basal ages of 6000-10,000 years, and are more common in the lowlands, particularly over floodplain or estuarine deposits. They can be found (and if anything have their greatest expression) in areas of low rainfall. Blanket

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mires are typically found in areas of high rainfall, and are extensive on upland plateaux in the UK, blanketing slopes up to 15°, but are also found close to sea level in western Eire; they are shallow, typically 0.5-3 m in thickness, and their basal ages range from 8000-1500 years.

2. PEATLANDS AND PALAEOHYDROLOGY

Ombrotrophic mires are particularly amenable to palaeohydrological study. Their deposits accumulate sequentially, and they remain incompletely decayed; so, over time, they become a stratified repository of evidence for past hydrological conditions. Contained within, and often clearly visible in the peat stratigraphy are the major hydrological and vegetational changes that occurred during their lifetime. It is this continuous, sequential character of their record that makes mires such an appropriate archive for palaeohydrologists.

The palaeohydrology of individual bogs can be investigated first by coring through their accumulated peat. Intact cores can then be recovered and analysed in the laboratory. Evidence in the peat for vegetational change includes both microfossils (such as pollen and rhizopods) and macrofossils (such as leaves and stems of plants). For example, pollen trapped in the peat is indicative not only of what was growing on the bog but also of the regional vegetation, which may give indications of palaeohydrological changes in the wider catchment.

Of the plants that commonly grow on bogs, some of the *Sphagnum* and other mire species show relatively narrow ecological tolerances, particularly with respect to mire-surface wetness, and so become confined to particular microhabitats; their position and relative abundance on the mire surface will be strongly influenced by the depth of the water table. On a growing mire, there is often a microtopography of hummocks and pools, sometimes with extensive 'lawns' of bog moss. During times of wetter climate, the surface of the bog will tend to be wetter, the pools may expand, and species preferring wetter conditions may be more abundant on the bog surface; whereas, during times of drier climate, the water table will be lower, the pools will contract, and so hummock-forming species may prevail. So, analysis of the abundant plant macrofossils in a vertical core of peat - particularly the remains of *Sphagnum* (bog moss), *Cyperaceae* (sedges) and *Ericaceae* (heathers) - allows a reconstruction of the relative importance of these taxa on the surface of the bog during past centuries. Detailed, quantitative analysis of the subfossil remains of these taxa in vertical cores of peat can indicate the past surface wetness of the bog, and so provide good palaeohydrological evidence covering several millennia.

The studies of plant macrofossils can be complemented by analysis of rhizopods; these are microscopic, mainly pool-dwelling animals whose remains become stratified in the peat, and whose presence as subfossils indicates wet conditions at the time of peat formation. Together, these techniques allow reconstruction of bog surface-wetness through time, and so provide palaeohydrological data.

In many blanket mires, and in other highly humified peats, macroscopic remains may be sparse. An alternative technique for reconstructing past hydrological changes is to determine the degree of peat humification - a measurement of the degree of breakdown of

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the peat (Aaby and Tauber, 1975; Blackford and Chambers, 1993). The decay or humification of peat proceeds much faster in drier conditions, and so peat laid down in dry or warm conditions will be more highly decayed, and appear darker in colour, than peat laid down in cool, wet conditions. These data largely record past changes in bog-surface wetness, and so are a direct palaeohydrological archive; but they also hint at past changes in temperature.

3. DATING AND TIME RESOLUTION

Depending upon their rate of growth, and on how finely the peat is sampled for analysis, bogs have the potential to provide information about hydrological changes on decadal or century timescales. Some of their contained subfossils - undecayed tree stumps, for example - may provide (in their tree rings) information on growing conditions for individual years, giving an immediate insight into the past hydrological conditions of a bog, thousands of years ago.

The most widely applied dating technique for peats is that of radiocarbon dating, but the many limitations of this method constrain the precise and accurate dating of palaeohydrological changes recorded in peat stratigraphy. Pilcher (1993) has warned that an individual, conventional radiocarbon assay is only accurate to the nearest half millennium; however, sequences of conventional radiocarbon ages on a vertical core of peat allow better dating control, and the radiocarbon ages can be calibrated to calendar years through the internationally recognised calibration curve (Stuiver and Reimer, 1986). Recent improvements in dating include high-precision radiocarbon dates, and the use of the 'wiggle-match', in which radiocarbon ages on successive contiguous slices of peat are matched to fluctuations in the radiocarbon calibration curve.

Exceptionally precise dates in peatland palaeohydrology may be given by documentary records of extreme events, such as 'bog bursts', when intense high-rainfall episodes might lead to such high water content in a bog that it 'bursts', with peat flowing over neighbouring land. Such episodes, though spectacular, are relatively uncommon. Their occurrence has the unfortunate consequence of disrupting peat stratigraphy and so destroying the previously continuous palaeohydrological record in the part of the bog so affected.

Precise correlation of peatland palaeohydrological records may in future be achieved through tephrochronology - the extraction and identification of fine volcanic ash shards in peats (Dugmore, 1989; Dugmore *et al.*, 1995). Some volcanic eruptions of the past two millennia are dated both accurately and precisely - to individual years - but their shards remain to be found in UK peats.

4. RECONSTRUCTING PAST CLIMATES FROM PEAT STRATIGRAPHY

The dependence of ombrotrophic mires upon rainfall has led to their being regarded as "directly coupled to the atmosphere" (Barber, 1995, p. 3), and it is believed that studies of their plant macrofossils can provide a very good indication of past climate. This type of work has been pursued by Barber (1981, 1982) and associates (Haslam 1987; Barber *et al.*,

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1994a; Barber *et al.*, 1994b) and is the basis of most detailed palaeoclimatic data from raised mires. Other techniques have also been applied (Aaby and Tauber 1975; Aaby, 1976; Brenninkmeijer *et al.*, 1982; Dupont and Brenninkmeijer, 1984; Dupont, 1985, 1986; Blackford and Chambers, 1993), including investigations of subfossil wood in peats (e.g. Dubois and Ferguson, 1985; Bridge *et al.*, 1990; Gear and Huntley, 1991; Pilcher *et al.*, 1995).

As an example, detailed studies of peat stratigraphy of a raised mire in northern England - at Bolton Fell Moss, Cumbria - have yielded 'proxy-climate' data that have been claimed to produce a sensitive, high-resolution record of climate change covering six millennia. The macrofossil data down the core can be summarised using ordination techniques to provide a time series of past bog-surface wetness, and the summary data show an oscillating record of change (Figure 1), reflecting the changing hydrology of the bog surface, but interpreted to indicate climatic changes (Barber *et al.*, 1994a; Barber *et al.*, 1994b).

Such studies are particularly relevant in the context of the current debate over 'global warming', as long reconstructions of past climate provide a baseline against which to test the alleged human-induced climatic changes of the present century. The instrumented record is, in geological terms, very short: instrumented meteorological records cover, at best, little more than 350 years, and so in order to understand the magnitude, rate and frequency of natural climatic and hydrological changes on a millennial scale, palaeohydrological data and 'proxy' data on palaeoclimates are crucial. Ombrotrophic bogs can provide such data (Barber 1981, 1982; Blackford 1993).

Detailed records of stratigraphic change in peat bogs were not exploited for climate reconstruction until the 1970s and 1980s, largely owing to a prevailing misconception as to how peat bogs grow (Backeus, 1990). Pool-and-hummock topography of raised mires was thought to be in cyclic evolution, in which pool species grew luxuriantly, peat accreted faster, and pools overtopped hummocks, and so themselves became hummocks, with the hummocks becoming pools. This notion of cyclic regeneration held sway for *c.* 50 years, from the 1920s, before being refuted finally by Barber in 1978 (see Barber 1981). So, it is only really within the last 20 years that the climatic signal from peat bogs has been seriously investigated; new findings are still emerging (see, for example, Blackford and Chambers, 1995).

5. BLANKET MIRES: PALAEOHYDROLOGY AND PALAEOCLIMATES

Data obtained on a transect of mires from Ireland to Poland suggest that raised mires on the western side of Europe, on its Atlantic seaboard, are more sensitive to climatic shifts, and give a more detailed proxy-climate record than those in continental Europe (Haslam, 1987). However, in this example, proxy-climate data from blanket mires will be used. Remembering the claimed sensitivity of mires on the oceanic margin of Europe, the locality investigated here is near Letterfrack, in Co. Galway, western Ireland. Contiguous 0.5 cm thick samples were analysed for peat humification from two peat profiles from sites 1.6 km apart, and samples were taken from each peat monolith for radiocarbon dating (Blackford, 1990). The overall trend is from high peat humification at depth, to lower peat humification at the surface. When the curves are detrended, an oscillating record of

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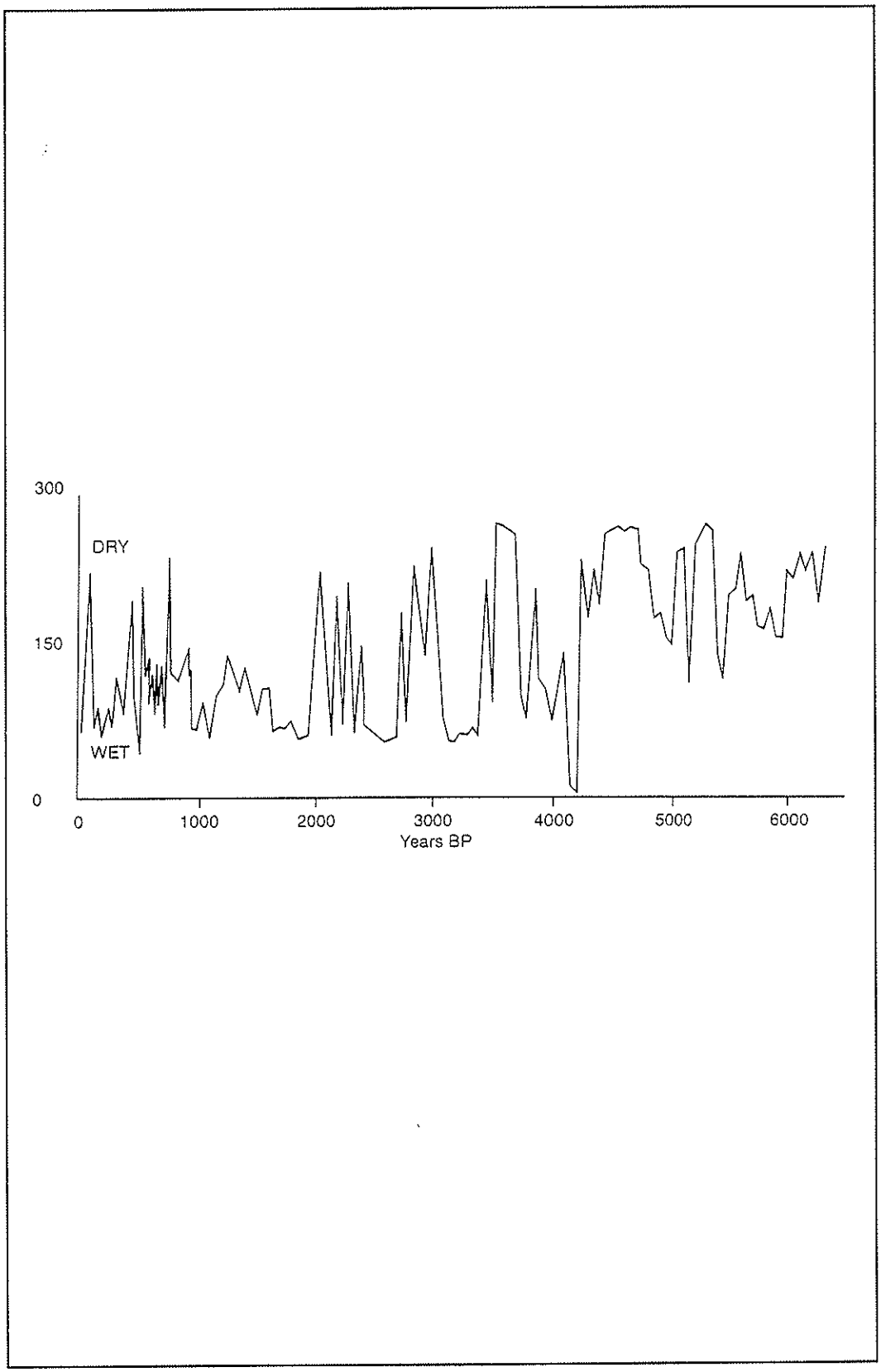


Figure 1 *Changes in bog-surface wetness for the past 6,300 radiocarbon years recorded in a core from Bolton Fell Moss, Cumbria: axis 1 DCA plotted against years BP (redrawn from Barber et al. 1994b, with corrections and additions).*

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climate change is revealed in both profiles.

The similarity between the two records is striking (Figure 2); it implies a regional, and probably a climatic cause. The data imply periods of drier (or warmer) climate in the period from *c.* AD 1050, turning wetter in the 1300s, and with periods of pronounced wetter (or cooler) climate in the periods *c.* AD 1410-1540, and *c.* AD 1660-1720. Drier (and/or warmer) climates may be inferred for the periods *c.* AD 1230-1380, *c.* AD 1560-1650, and *c.* AD 1730-1780 (Blackford and Chambers, 1995). What is interesting about these data is that they show parallels with historical records and with other proxy-climate records for the Medieval Optimum in north-west Europe (of the late 11th to 13th Centuries AD), for a downturn in the 1300s, and, to an extent, with evidence for the so-called Little Ice Age of the 16th to 18th centuries AD. This is not the only point of interest.

The data show two significant periods of wetter or cooler climate in the past 600 years, and these apparently coincide with the Sporer and Maunder minima in solar activity (Stuiver and Quay, 1980). The apparent relationship between the two proxy-climate records from Letterfrack and the reconstructed sunspot record, especially in the period from AD 1650 to the present, suggests a link between changing bog hydrology in western Ireland and solar variability. One way to explain this is to consider that, in periods when sunspot frequency increased, summer anticyclonic conditions prevailed over north-west Europe, resulting in a warmer and drier climate over western Ireland; during periods of sunspot minima, effective insolation decreased, cooler/wetter conditions prevailed, and less-humified peat accumulated (Blackford and Chambers, 1995).

6. PALAEOHYDROLOGICAL INTERPRETATIONS OF SUB-FOSSIL PINE REMAINS IN MIRES

Many mires in the British Isles contain wood macrofossils. Indeed, some mires appear to have been colonised in prehistory by cohorts of Scots pine - the wood macrofossils are large, and analysis of their tree-rings shows that some of the trees were long-lived. At Sluggan Bog, Co. Antrim, three generations of pine stumps have been found dating from *c.* 6000 Cal. BC (*c.* 7200 BP). The overall chronology of these subfossil pines lasts some 809 years, and probably spans the period from *c.* 6300-5500 Cal. BC. (Pilcher *et al.*, 1995). A more recent phase of pine growth on many raised bogs in the north of Ireland centres on 3000 BC. Cross-dating with the Belfast bog-oak chronology shows that it spans the period 3451-2569 BC (Pilcher *et al.*, 1995). This period of pine growth apparently ceases *c.* 4000 BP (i.e., *c.* 2500 Cal. BC), which is similar to records for pines on raised mires in central Ireland (McNally and Doyle 1984) and beneath blanket mires in Scotland (Bridge, Haggart and Lowe 1990; see also Gear and Huntley 1991). However, on the Welsh border, at Fenn's and Whixall Moss, an episode of pine growth occurred more recently, during the period 3200 to 2900 BP (*c.* 1443 - 1045 Cal. BC) (Grant, 1995; Chambers *et al.*, in press).

These remains of subfossil pine imply that there have been significant changes in bog hydrology in prehistory. However, apart from recent pine colonisation of partially drained mires, no bog-pine episodes are known to date from the last two millennia in the British Isles, but this may in part be because tree growth would have been inhibited by cultural activities, such as the intermittent burning and grazing of mire surfaces since late-

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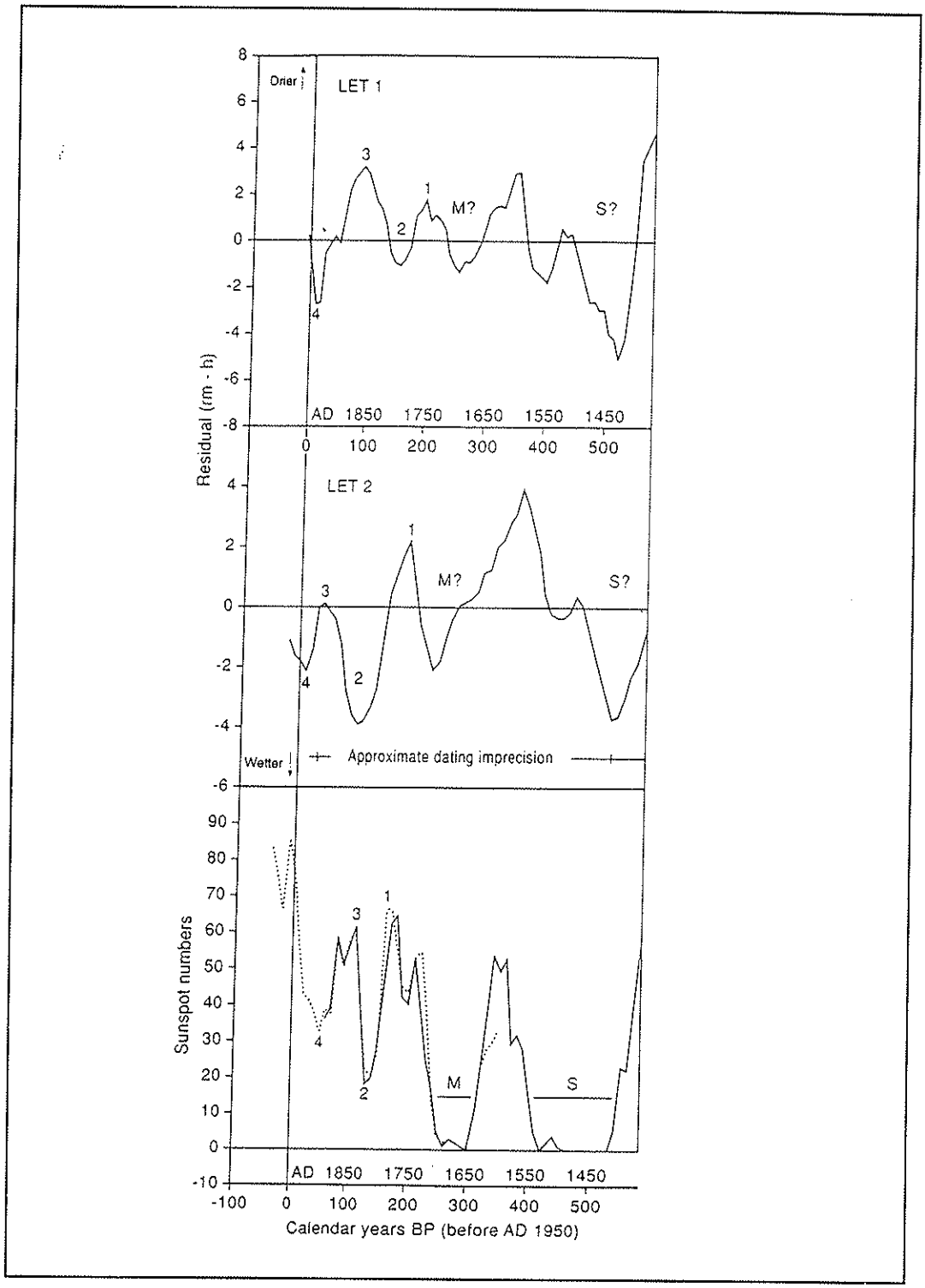


Figure 2 *Residual, detrended peat humification data from Letterfrack profiles LET 1 and LET 2, plotted above the estimated (solid line) and observed (broken line) sunspot numbers for the last 600 years, and apparently showing a good match. Dating imprecision for the peat profiles increases with age; the period beyond 600 years does not show as good a match, perhaps because of poor geochronological control (reproduced from Chambers, 1995, based on Blackford and Chambers, 1995).*

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prehistory (Chambers, forthcoming).

The cross-matching of tree-ring sequences to form long chronologies, and the study of tree ring-widths in those chronologies allows inferences to be made about climate through 'dendroclimatology'. In Fennoscandia, dendroclimatological studies on modern, ancient and subfossil pine show a highly variable climate there, with inferred July/August mean temperature variations of more than 2°C over the past few thousand years, with century-timescale variation (Briffa, 1994). The temporal precision and accuracy possible in studies of tree-rings - with data available for individual years and, potentially, for short-term changes even within the growing season (Loader *et al.*, 1995) - contrasts with the, at best, decadal-to-century precision in studies of other macrofossils from peats.

7. IMPLICATIONS FOR CONTEMPORARY HYDROLOGISTS

In short, the palaeohydrological data from bogs imply (1) that, during the Holocene in parts of the British Isles, there appear to have been periods of relative warmth or dryness, alternating with periods of relative wetness or coolness; (2) that some of these changes might be linked with solar variability (cf. Friis-Christensen and Lassen, 1991; Kerr, 1991; Bradley *et al.*, 1995); (3) that some short-lived but significant hydrological changes were apparently sufficient to have allowed bog-pine growth on particular mires, and that climatically driven bog-hydrological change may then have caused their demise; and (4) that there has been a highly variable climate over the past few thousand years - climate variability seems to be the norm (Chambers, 1995).

The implications for contemporary hydrologists can now briefly be explored. As the bog hydrological data show periods of relative dryness, interrupted by periods of relative wetness, this implies that there is no 'normal' climatic regime in the Holocene. Thirty years of records, such as is used for comparative purposes by the Meteorological Office, can represent neither the norm nor the extremes of climate variability; the concept of a 'normal' climate is therefore insufficient as a basis for hydrological or water resource planning. Even the analysis of recent centuries of hydrological data, or of instrumented meteorological records, do not show fully the extremes of climate possible in the late Holocene. The palaeohydrological data from bogs show an oscillatory record. Hence, simple notions of magnitude and frequency, particularly of 'return periods' for individual hydrological events, may be gravely misplaced. Rather than the 'event' occurring, say, once in a 100 years, or once in 500 years, it may be more likely that high-magnitude events will be found closer together; the return period is not for the event (singular), but for the likely occurrence of such events (plural); high-magnitude events may occur in bunches, separated by periods of relative quiescence.

8. CONCLUSIONS

In summary, in the last two decades there has been a great deal of work on the palaeohydrology of bogs in the British Isles, much of this linked with the reconstruction of past climates. It would probably be helpful if the palaeohydrological data from these recent studies were drawn to the attention of contemporary hydrologists, and that the variability in the palaeoclimatic record became more widely known and their implications

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appreciated, perhaps particularly by planners, by civil engineers and by insurers, but also by the public at large.

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Palaeohydrogeology: unravelling the evolution and past dynamics of aquifer systems

P L Younger
Department of Civil Engineering, University of Newcastle

Abstract

Palaeohydrogeology is the science of unravelling the evolution and prehistoric dynamics of aquifer systems. As such it is concerned with aquifer genesis, and estimates of prehistoric aquifer budgets (water inputs, throughputs and outputs). For purposes of definition, it is convenient to regard "aquifer genesis" as embracing those processes which were complete (or nearly so) before the current phase of active meteoric groundwater circulation commenced. In general terms, the genesis of clastic aquifers is primarily explained by depositional sedimentology, and the genesis of carbonate aquifers by dissolutional weathering. Tectonic processes have received less attention in most aquifer genesis studies, despite their critical importance in imparting fracture porosity. Even though modern-day aquifer recharge is difficult to estimate, there do exist a number of methods for estimating recharge in former times. If it can be assumed that long-term palaeo-recharge was in equilibrium with discharge, then estimates of aquifer discharge (from analyses of the sedimentary records of springs) can be used to infer palaeo-recharge. It is also possible (though hazardous) to make semi-quantitative palaeo-recharge estimates from proxy climatological data. In carbonate karst systems, speleothems can record temporal variations in recharge rate. Finally, in certain cases (especially in arid lands) remnant piezometric depressions and vertical hydrochemical profiles record past episodes of recharge. Former groundwater flow patterns are often inferred indirectly by considerations of the changes through time in the positions and elevations of base-level drainage controls (e.g. large perennial river, or the coastline). Direct evidence of past groundwater flow directions are afforded by zones of fissure enlargement associated with former water table positions in carbonate rocks, and by the presence of aligned concretions in some clastics. Vadose and phreatic dissolution / precipitation features (caves and cements respectively) can be used to infer the fluctuations in saturated conditions through time. Direct evidence of former groundwater discharge is afforded by the occurrence of sedimentary deposits associated with springs and seepages. Travertines are the most common sedimentary deposits associated with discharging groundwater, but clastic spring deposits ("sand cones") have recently been discovered in East Yorkshire. Indirect evidence of groundwater discharge is preserved as buried coastal features, lake-shores or perennial river channels; interpretation of the latter two in particular requires considerable care. System variables,

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in particular "palaeohead" values, can be determined by dating and careful surveying of travertines, sand cones, hardpans, groundwater gleys, relict karst resurgences, lake and sea shore-lines and river terraces.

1. INTRODUCTION

The prediction of effects of future climate changes on aquifers requires an appreciation of long-range transient processes which are outwith the record of conventional hydrological time series. If climate change increases recharge, for instance, we can confidently expect a rise in groundwater levels; in many unconfined aquifers, this may lead to saturation of subsurface zones which have never been saturated in human history, and for which we therefore have no test-pumping data. Conversely, a reduction in recharge might lead to a drop in groundwater head, and to increased circulation in subsurface zones which formerly experienced more sluggish groundwater flow. In either case, the aquifer would respond in a manner which falls outside of the range of descriptions based on existing hydrological data. Furthermore, if we attempt to predict aquifer responses to variable recharge over centuries or millennia, then the usual assumption of time-invariant porosity and permeability will often be violated. Even slow geochemical reactions will have a significant cumulative effect on aquifer configuration (mineral precipitation destroying porosity, mineral dissolution increasing it) over long time periods.

These problems pose a fundamental challenge to all who would develop (and hopefully test) models for predicting the effects of climate change on groundwater systems. One response to this challenge is to test the ability of such models to reproduce aquifer evolution through geological time. This pre-supposes that we have some means of unravelling aquifer history. The means is the infant sub-discipline of palaeohydrogeology.

This paper briefly summarises some key notions in palaeohydrogeology. It is intended to serve as a brief guide for scientists hoping to establish histories for specific aquifers. In no sense is this paper intended to be an exhaustive review of the literature (though such a review would clearly be useful in the long term); rather it is a compendium of ideas supported by useful, recent published examples.

2. AQUIFER GENESIS

In general, the issue of "aquifer genesis" has not been accorded much attention by hydrogeologists. While petroleum geologists have profitably expended much energy on deriving facies models for reservoir rocks, with the intention of constraining predictions of aquifer geometry and poroperm variations, little effort has been made to apply similar principles to hydrogeological studies. This is in part because complex near-surface geological processes (primarily weathering and the formation of extensional joints as strata are uplifted and eroded) are so important in determining aquifer properties that well-known processes of deposition and diagenesis often assume secondary importance. (By contrast, deeply-buried petroleum reservoirs can often have negligible fracture permeability, and production potential is governed much more closely by depositional fabrics and diagenetic history.)

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Where significant deposition of clastic sediments has occurred during the Quaternary, generating shallow aquifers, considerable attention has been paid to aquifer genesis. Glacial sediments have been widely studied by American workers. Pettyjohn and Randich (1966) investigated the use of lithofacies maps of glacial sediments in hydrogeological studies. Kehew and Boettger (1986) investigated the influence of depositional environment of Pleistocene buried valleys in North Dakota on development of conceptual hydrogeological models. Most recently, facies models for continental glaciation have been used by Anderson (1989) as an aid in preparing data sets for groundwater flow models.

Periglacial erosion and sedimentation during the Quaternary have had mixed hydrogeological consequences. Coarse clastic sediments (of both glaciofluvial and periglacial origin) are generally of braided-river facies. Standard facies models for coarse clastic sediments have been adopted by Dixon *et al.* (1989) as the framework for assessing heterogeneities in the aquifer properties of the arctic nival Thames floodplain gravels. Extensive field and laboratory testing has allowed the definition of characteristic hydraulic parameter values for individual lithofacies units. This information has been used in constructing mathematical flow and transport models for the Thames gravels. A similar approach has been taken by Jussel (1989) who worked on fluvial gravel deposits in the Alpine foreland.

Quaternary cryogenic sediments, formed by freeze-thaw and concomitant mass movement processes ("gelifluction"), have very variable hydrogeological properties, which depend on the nature of the parent material, and the thickness of the accumulated sediment. For instance, where periglaciation has affected the relatively soft southern English Chalk, gelifluction deposits (commonly termed Chalk "head"; Catt, 1988) the uppermost surface of outcropping Chalk is typically mantled by a dense breccia (fragments of chalk in a very fine-grained matrix) or by structureless "putty chalk" (sometimes termed "Grade IV melange chalk" by geotechnical engineers). By contrast, the hard Chalks of northern England have often yielded loose, open gravels in response to gelifluction. Such periglacial gravels are an important element of the Chalk aquifer system in East Yorkshire and Lincolnshire (Younger, 1992a; 1993a).

In the tropics, patterns of Quaternary sedimentation have also been linked to aquifer genesis. Younger (1992a), working in the Bolivian Altiplano, successfully applied photogeological methods to interpret Quaternary depositional systems associated with an extensional re-activation of a buried Oligocene thrust-front. Delineation of a zone of sandy deposition, associated with the fault scarp and tilting of the footwall and hanging-wall fault blocks, allowed delineation of a major hydrostratigraphic unit which has since been exploited by irrigation wells.

Genesis of carbonate aquifers (Brahana *et al.*, 1988) is typically considered to involve depositional processes (Hanshaw and Back, 1979), diagenesis (Whitaker and Smart, 1990), fracturing, and development of permeability by dissolution (Rhoades and Sinacori, 1941; Stringfield *et al.*, 1979; Younger, 1989; Panno and Bourcier, 1990). Much valuable conceptualisation of carbonate aquifer genesis has been pursued under the *aegis* of speleogenesis and karst development (recently reviewed by Lowe, 1992a). Most theories of carbonate aquifer genesis may be summarised by saying that dissolutional development of permeability arises either where flow or geochemical reactions are focused in a given zone. In the case of flow, focusing may arise:

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- simply from the convergence of groundwater flow lines towards discharge areas (Rhoades and Sinacori, 1941);

- by preferential flow exploiting tectonic fracture zones, such as those extensional fracture zones which commonly occur in anticlinal axes (Stringfield *et al.*, 1979);

- due to natural variations in permafrost configuration during cold periods (Younger, 1989; 1993a).

Lowe (1992b) has developed the theory of "inception horizons" which embraces such physical features as well as zones which are geochemically prone to give rise to dissolution. For instance, where gypsum beds or pyrite nodules occur, dissolution might be expected to occur more readily (due to the common ion effect in the former case, and neutralisation of acid in the latter). In many ways, the classic "inception horizon" is the zone of mixing between fresh and saline groundwaters, for here we have both focused flow and a geochemical predisposition to dissolution (Hanshaw and Back, 1979). An interesting example of Pleistocene speleogenesis in a fresh/saline mixing zone has been outlined by Panno and Bourcier (1990). They argue that expulsion of saline groundwaters from deep aquifers (in response to compaction under the weight of a continental ice sheet) led to development of mixing zones in the shallow subsurface in the American Mid-West. Caves then formed rapidly in this zone.

Tectonic processes have received less attention than depositional and early-diagenetic processes in most aquifer genesis studies. Apart from the widespread use of photogeological and remote sensing methods to search for tectonic lineations with potential hydrogeological importance in areas of crystalline basement, there appears to have been no coherent integration of structural geology and hydrogeology to date. An attempt by Farhoudi and Poll (1992) to apply regional tectonic terrane evaluation techniques to hydrogeological mapping was largely unsuccessful (Younger, 1993b). At the site scale, fracture system characteristics can be analysed statistically (e.g. Dershowitz and Einstein, 1988), and the results of such analyses can be used in developing flow and solute transport models (Chilès and Marsily, 1993). However, there is as yet no unifying theory which can predict even simple orthogonal joint system characteristics from lithology and tectonic setting alone. This is clearly a drawback for aquifer genesis studies, as initial conditions are difficult to establish. This remains a subject area ripe for research, and one which has clear relevance for the development of genetic models for secondary permeability in carbonate aquifers.

There is a difficulty in deciding where "aquifer genesis" ends and "aquifer development" begins. This is especially true in the case of carbonates; depositional and early diagenetic fabrics are often of little importance as determinants of aquifer properties in most limestones older than Tertiary age. Hence the enlargement of joints and other discontinuities by groundwater flow ("development") is often the primary source of major permeability ("genesis"). A solution to this problem may be sought by recourse to geological history. For purposes of definition, it is convenient to regard "aquifer genesis" as those processes which were complete (or nearly so) before the current phase of active meteoric groundwater circulation commenced. In the case of cold-climate Quaternary deposits, for instance, active circulation was restricted to thin thawed zones until the end of the last stadial (Younger, 1989; 1993a). For older rocks (including most European

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carbonate aquifers) uplift during the latter phases of the Alpine orogeny (in the Tertiary) marked the onset of meteoric groundwater circulation. On this basis, we will restrict our discussion in the following sections to aquifer development and palaeo-hydrodynamics.

3. INPUTS: ESTIMATING "PALAEO-RECHARGE"

Groundwater recharge to most present-day aquifer systems is notoriously difficult to quantify (Lerner *et al.*, 1990). On the face of it, therefore, there would seem little hope of deriving reliable estimates of groundwater recharge for prehistoric conditions. Nevertheless, there are a number of methods available for estimating recharge in former times; these are briefly outlined below.

Wherever we can reconstruct past aquifer discharge rates for a given period in prehistory (for examples, see Section 4 below), an approximate assessment of recharge can be made. This is simply because change in groundwater storage will be negligible over short time periods, so that the general water balance equation:

$$R - D = \Delta S \qquad (1)$$

will reduce to:

$$R - D = 0 \qquad (2)$$

As anthropogenic influences on groundwater storage are negligible before the 16th century, thus reducing the uncertainties in defining a temporary steady-state, such an approach theoretically has considerable potential. However, this kind of analysis could only be made as part of a major regional palaeohydrogeological investigation, which would involve application of many of the techniques detailed in the rest of this paper.

An alternative approach to palaeo-recharge estimation, and one which does not demand *a priori* knowledge of overall aquifer budgets, involves studying surrogate rainfall (or at least relative humidity) records. For instance, Lamb (1977) used diverse historical records to reconstruct climatic changes for England over the period 1100-1850 AD. Less detailed historical records, archaeological remains, and clues from Holocene sediments, were used by Lamb (1982) to extend this record of climate change to pre-historic periods. This record was used by Younger and McHugh (1995) to constrain palaeohydrogeological reconstructions for the East Yorkshire Chalk. Adopting the temperature-rainfall correlation presented by Lamb (1977), Lockwood (1979) produced an outline water balance for Britain over the last 50,000 years. This water balance was adopted by Hiscock and Lloyd (1992) for modelling of the palaeohydrogeology of the north Lincolnshire Chalk.

Where archaeological and historical records are scarce, palaeoclimatic reconstruction is best approached by studying sediments and their enclosed floral, microfloral, and faunal material. For instance, in many climatic zones, the sedimentology, palaeoflora and palynology of lake sediments can record substantial changes in rainfall and evaporation over time. Thus in the arid Atacama desert of northern Chile (Grosjean, 1994), the sedimentary succession of Laguna Leija (a lake in a small hydrologically closed basin) records a period around 13,500 - 11,000 BP during which rainfall was more than 100%

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higher than at present. These estimates were derived by applying a water and energy budget model to the region, simulating the climatic scenarios which could have resulted in the observed sedimentation patterns and lake water levels (recorded as abandoned shorelines). In the humid, temperate zone, a warm and dry mid-Holocene climate (mean July temperature 1°C higher than at present, rainfall 10% lower) has been deduced from the sequence of clastic and carbonate muds (and enclosed pollen and plant remains) found in Rice Lake, Ontario (Yu and McAndrews, 1994).

High-resolution climatic change records have been obtained by analysing the changing proportions of plant taxa through time in peat deposits in northern Britain, Ireland, Denmark and Germany (Barber *et al.*, 1994). In the well-documented case of Bolton Fell Moss, Cumbria, UK, plant taxa proportions for peats younger than a thousand years were compared with the detailed historically-based climatic record of Lamb (1977). A close correlation between taxa proportions and relative wetness/dryness was found. On the basis of this correlation, the surrogate high-resolution climate record was extended back into prehistory (to almost 7000 BP).

In carbonate karst systems (and, presumably, to a lesser degree in karsts of different lithology) speleothems can record temporal variations in recharge rate. An annually-layered stalagmite from Drotsky's Cave, northwestern Botswana, records variations in rainfall and air temperature (Railsback *et al.*, 1994). Each year a layer of euhedral calcite is formed during the period of active recharge. As recharge wanes, the calcite crystals assume flatly terminated forms, and with the onset of the dry season, the modal mineralogy changes to aragonite. Annual bimineralogical layers of this sort yield more detailed palaeoclimatic information than the superficially analogous (and more widespread) study of tree-rings. Even without detailed mineralogical studies, speleothem records can provide valuable palaeoclimatic records. Gordon *et al.* (1989) studied the past variation in speleothem growth frequencies in England. The dated growth frequency curve which they produced provides an impressive record of relative recharge intensity (though not absolute magnitude) for the last 140,000 years. Hiscock and Lloyd (1992) used this curve to constrain palaeohydrogeological reconstructions for the Chalk aquifer of north Lincolnshire, UK.

Aquifer piezometry may, under special circumstances, preserve evidence on recharge history. For this to be possible, a combination of low hydraulic conductivity and a low modern rate of recharge seems to be necessary. For instance, Dieng *et al.* (1990) describe large-diameter natural cones of depression in the water table within the Senegal sedimentary basin in western Africa. These depressions were apparently formed by a general lowering of the water table during a lowstand of the sea in the Pleistocene, followed by partial recovery in coastal groundwater levels in response to Holocene sea level rise; low hydraulic conductivity and negligible recharge inland have prevented the resulting depressions from filling to date (Dieng *et al.*, 1990). Cautious interpretation of such features is warranted in areas of active tectonism, however, where natural depressions in the water table may be due to neotectonic uplift / depression of the rock mass (Custodio, personal communication, 1995). Indeed in the vicinity of Barcelona, piezometric depressions in an (un-pumped) low permeability zone of a carbonate aquifer have been ascribed to the effects of explosions associated with quarrying (Custodio, 1975).

In some cases, it is possible to use the hydrochemistry of waters currently resident in

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aquifers (especially the dissolved noble gases and various radioisotopes) to deduce the timing of recharge, and indeed the temperature of the water at the time of recharge (Elliot, 1990). Residence times for waters revealed by such analyses are often significantly longer than those which would be predicted by simple advection modelling, illustrating the complexities of interaction between fast and slow flow domains within dual-permeability systems.

Hydrochemical profiles obtained by analysing centrifuge supernatants obtained from unsaturated zone core material can have considerable palaeohydrogeological value (Cook *et al.*, 1992). By application of appropriate models, it is possible to use such hydrochemical profiles in areas with thick unsaturated zones to estimate palaeo-recharge and palaeoclimate. Estimation using this approach has been undertaken for a number of sites in Africa and in Mediterranean Europe (Cook *et al.*, 1992).

4. THROUGHPUTS: EVIDENCE OF FORMER GROUNDWATER FLOW PATTERNS

Former groundwater flow patterns are often inferred indirectly by considerations of the changes through time in the positions and elevations of features which control discharge from the aquifer (e.g. large perennial river, or the coastline), and therefore exert a powerful base level influence on the development of aquifer piezometry. As we will discuss base level changes in Section 5, no more need be added at this point.

Direct evidence of former groundwater flow, preserved either in the aquifer materials or in the disposition and quality of the groundwaters themselves, is rather more difficult to come by, and presents substantial interpretational problems. Often, direct evidence of this kind cannot provide an unequivocal indication of former groundwater flow patterns in the absence of other evidence. However, where palaeo-recharge areas and/or palaeo-discharge areas have been identified, the types of evidence listed below can provide powerful substantiation of an evolving palaeohydrogeological interpretation of an aquifer.

In carbonate rocks, the best evidence of former groundwater flow patterns is usually afforded by the presence of virtually horizontal zones of fissure enlargement associated with a former zone of water table fluctuation. For instance, three such zones (or "surfaces") occur within the East Yorkshire Chalk aquifer. One zone corresponds with the modern zone of water table fluctuation. The second zone lies within the saturated zone, approximately 20 m below the modern water table zone. Finally, a dewatered fissure zone has been encountered about 20 m above the modern water table zone. When modelling the palaeohydrogeology of part of the East Yorkshire Chalk, Younger and McHugh (1995) found that this uppermost zone probably corresponds to the zone in which the water table fluctuated around 5800 BP.

In the absence of planar zones of this nature, the forms taken by caves in karst aquifers can be used to indicate the former water table position. Caves formed below the water table ("phreatic tubes") generally have a roughly circular (or tear-drop) cross-section, arising from the equal water pressure exerted on all cave walls during dissolution. On the other hand, caves which have been eroded above the water table ("vadose passageways") are characterised by a "keyhole" profile, due to fluvial down-cutting of the cave floor by

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intermittent cave stream flows (Ford and Williams, 1989). Frequently, originally phreatic forms are found to have been subsequently modified into vadose forms as the water table has dropped. The uppermost limit of vestigial phreatic forms gives an indication of how high up the sequence the water table has formerly lain.

Direct dating of such forms in carbonate aquifers is difficult, and in many cases may only be possible where other forms of evidence can be used to constrain possible phases of karstification (cf. Younger and McHugh, 1995). Where caves are large enough to permit human entry, speleothems which have developed in vadose passageways after the water table has dropped may be dated by uranium-series and radiocarbon methods to provide a minimum age at which unsaturated conditions were established. By further extension of this principle, fluctuations of the water table in a coastal karst aquifer have been related to oscillations in the level of the Mediterranean sea by stratigraphically dating 13 layers of phreatic cement which successively accumulated in coastal caves of Mallorca (Ginés *et al.*, 1981; Pomar, 1989).

In clastic rocks, large-scale dissolution zones are unlikely to be encountered (although karst forms - presumed to have been formed predominantly by mechanical erosion - are occasionally encountered; Younger and Stunell, 1995). However, in both clastic and carbonate rocks, micro-scale features can record the former position of the water table. Sedimentary petrologists habitually distinguish between cement phases believed to have been formed in the saturated and unsaturated zones (Younger *et al.*, 1986). Cements formed in the saturated zone ("phreatic cements"; Figure 1(a)) are generally characterised by euhedral crystals, forming a coating of approximately equal thickness ("isopachous fringes") on all the grain surfaces surrounding a pore. Terminations of euhedra extend into the pore space from all sides. By contrast, cements formed in the unsaturated zone ("vadose cements"; Figure 1(b)) show an uneven distribution on grain surfaces around pores, and frequently display two forms:

(i) Pendant forms, which are essentially "micro-stalactites", formed by water droplets hanging down from grains.

(ii) Meniscus forms, which form arcuate infills at grain contacts, corresponding to water which has been held by suction forces (which are strongest around grain contacts).

These phreatic and vadose cements are commonly encountered in both clastic and carbonate rocks, and are particularly well displayed in travertines of carbonate or sulphate composition (Donovan *et al.*, 1988). Identification of the position within a sequence at which the form of a given cement phase changes from vadose to phreatic form allows identification of former water table positions. Sharp and McBride (1989) discuss other possible applications of sedimentary petrology in palaeohydrogeological reconstructions, though (disappointingly) the case studies they present relate primarily to sub-marine groundwaters.

There is strong evidence to suggest that elongate concretions found in many sandstones record the former direction of groundwater flow (McBride *et al.*, 1994). The long-axes of such concretions tend to develop parallel to the groundwater flow direction. It should be noted, however, that the orientation of concretions gives only the azimuth along which

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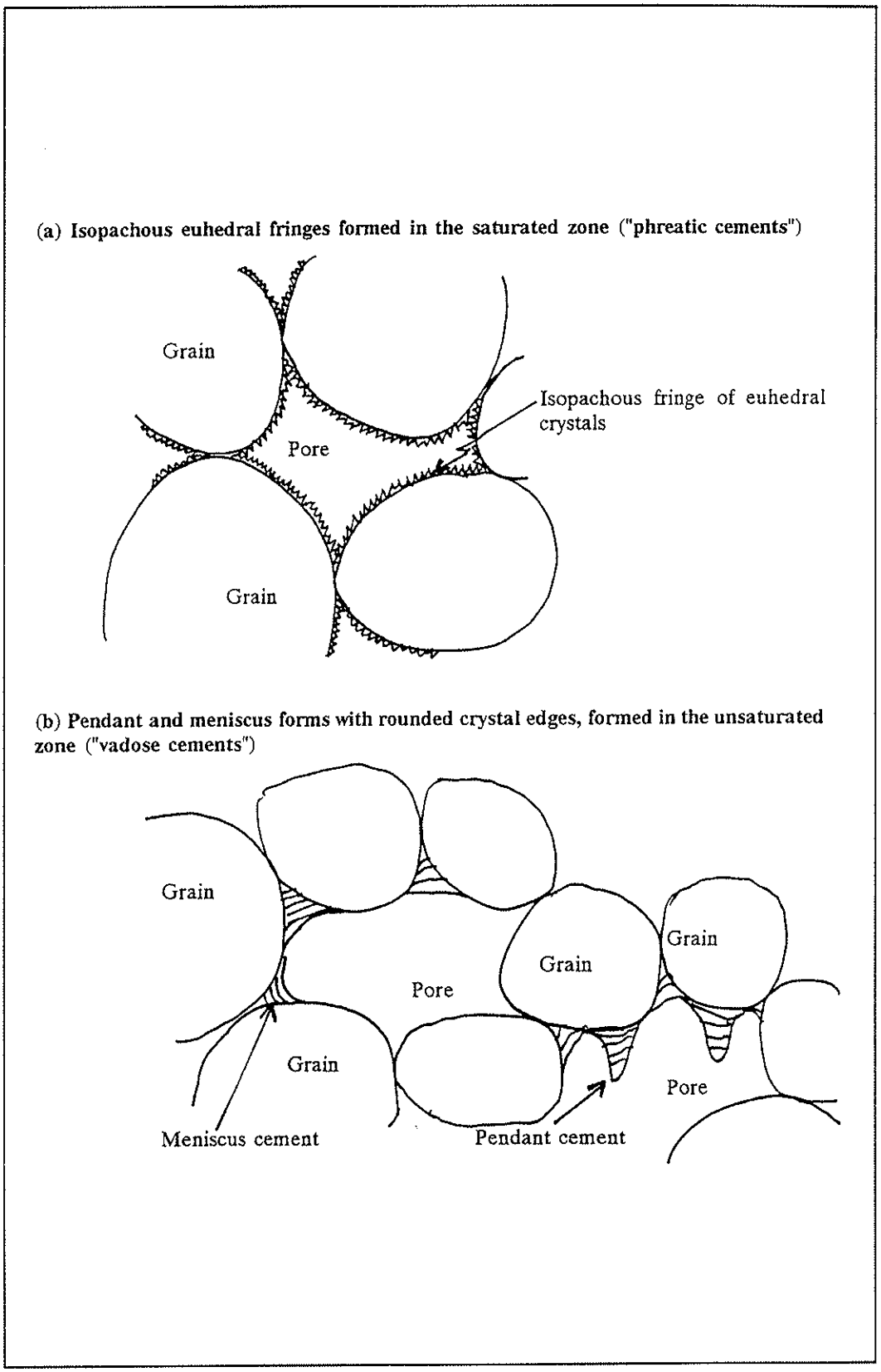


Figure 1 Cement textures indicative of formation in the saturated and unsaturated zones

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flow occurred, and not the sense of motion (e.g. we might deduce that flow occurred along a line trending 45°N from the observation point, but we cannot deduce whether the former flow was towards 45°N or towards 225°N). However, given a knowledge of the azimuth, the search for laterally equivalent geological features which might have controlled groundwater discharge (e.g. a major channel sandbody) can be narrowed, and absolute direction of flow might be discerned. It should be stressed that elongate concretions in any one formation might be of varying ages, and that an elongate profile can develop due to post-diagenetic structural deformation. In the example given by McBride *et al.* (1994), however, these complications did not arise, since the host sediments are geologically young and largely unconsolidated, and are disposed in a coastal plain where groundwater flow directions have clearly been constrained into a consistent direction for many millennia due to the base-level control exerted by the Mediterranean Sea.

In soils and palaeosols, groundwater gley features record former periods of saturation (PiPujol and Buurman, 1994). Groundwater gley in soils is typified by a dark (reduced) soil matrix, with reddening (ferric iron staining) along the major macropores. By contrast, surface-water gleys (formed in the unsaturated zone) show reddened (haematite stained) matrices, with bleached macropores (PiPujol and Buurman, 1994). The transition zone between these two gley types in palaeosols corresponds to the former water table position. However, caution must be exercised in deducing regional palaeohydrogeological conditions from observations on only a few exposures of gley transition zones, since the same pattern can be formed under perched groundwater conditions in zones where interflow is important. Iron hardpans frequently form on the water table in coarse clastic sediments too, particularly in groundwater discharge zones, where relatively reduced iron-bearing groundwaters encounter increased aeration at the water table (Younger, 1990). Thus identification of gleys and hardpans can greatly assist in reconstruction of former groundwater flow patterns.

Finally, it is possible to use hydrochemical facies distributions and geochemical groundwater age information to deduce former groundwater flow directions in many cases (Elliot, 1990; Hiscock and Lloyd, 1992).

5. OUTPUTS: EVIDENCE OF FORMER GROUNDWATER DISCHARGE

Direct evidence of former groundwater discharge is afforded by the occurrence of sedimentary deposits associated with springs and seepages, or with diagenetic features which record the former position of the water table. Indirect evidence is preserved as buried coastal features, lake-shores or perennial river channels; interpretation of the latter two in particular requires considerable care, but in the appropriate context they can provide important constraints on the development of a palaeohydrogeological reconstruction.

The classic sedimentary products of groundwater discharge are travertines. The name is derived from the splendid carbonate spring deposits ("Tiburtinus") which occur alongside the Tiber river near Rome (Chafetz and Folk, 1984). The term "tufa" is sometimes used as a synonym for travertine, but it is ambiguous since sheet-like mineral deposits formed in caves are also termed tufas (but never travertines). Most travertines are calcitic, and this has lead some geologists to consider that the term "travertine" is applicable only to carbonates deposited by springs. However, the unique feature of any travertine is that it is

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a chemical precipitate formed by discharging groundwater. Hence logic suggests that the term travertine is applicable to any chemical precipitate formed by springs. Thus barite ($BaSO_4$) travertines have been described by Younger *et al.* (1986) and Donovan *et al.* (1988). Silicic travertines are also known, and numerous other possibilities exist.

Travertines of any composition tend to display similar fabrics, notably terracettes, rim-stones and various domal structures (Chafetz and Folk, 1984; Younger *et al.*, 1986; Pentecost, 1993). The similarities of some of these features to the fabrics displayed by carbonate thinolites (confusingly regarded as a type of tufa by Benson, 1994), which are essentially evaporitic carbonate mounds formed in and around some lakes, demands that caution be exercised in interpreting older travertine-like deposits (where the relationship to present or former groundwater discharge is unclear). Goudie *et al.* (1993) have observed that travertine deposition appears to have become less common during the last 2500 years. Examples are drawn from central Europe, from the Swabian Alb in Germany, and from various sites in Britain. The decline might be due to increasing dryness during the late Holocene; it is unclear whether human impacts (due to deforestation etc) are important. Further research on this point is urged by Goudie *et al.* (1993); such research has considerable importance for the development of palaeohydrogeological reconstructions.

At the sites of individual travertine deposits, various phases of deposition are commonly noted. Phases of discharge are often dateable, for the travertines commonly incorporate substantial amounts of algal material and other organic matter. The elevations of travertine terraces associated with different phases of spring activity can yield clues about palaeo-piezometry (Figure 2). Where younger terraces are generally higher than older terraces, a gradual increase in groundwater levels is implied (Figure 2(a)). In extensive aquifers, this may reflect a regional groundwater level rise. However, in aquifers of limited lateral extent, the groundwater level rise may simply be a local effect, arising from the choking of the discharge area with travertine. This can lead to a local rise in groundwater level, which will stabilise when a higher outflow point is reached. This is the case at the Shotton travertine in County Durham, UK. On the other hand, some travertines display progressively lower terraces through time (Figure 2(b)). For instance, the barite travertines at Zodletone, Oklahoma, described by Younger *et al.* (1986) display this trend; this is considered to reflect gradual waning of regional groundwater head in the Anadarko Basin, from which the groundwaters emerging at the springs are considered to be flowing (expelled by basinal compaction).

Travertines are the most common sedimentary deposits associated with discharging groundwater, but clastic spring deposits are also known. Initially postulated by Guhman and Pederson (1992), the first positive identification of such features is thought to be reported by Younger and McHugh (1995). An archaeological dig near Beverley, UK, revealed humified peat enclosing conical and cylindrical sand bodies ('sand cones'), which contained Romano-British greyware. Below the peat, upper and lower diamict units (previously classified as Holocene alluvium) were reclassified as Late Devensian lodgement till and pre-Late Devensian chalky head (gelifluction deposits) respectively. Enigmatic buried timbers, dated dendrochronologically to 5840 BP, were found partially buried within the till. Micromorphological evidence shows that the peat is autochthonous. The sand cones are remains of former spring orifices, which served as foci for groundwater discharge from the regional East Yorkshire Chalk aquifer (which underlies the chalk head deposits in hydraulic continuity). As a corollary, it is suggested that the

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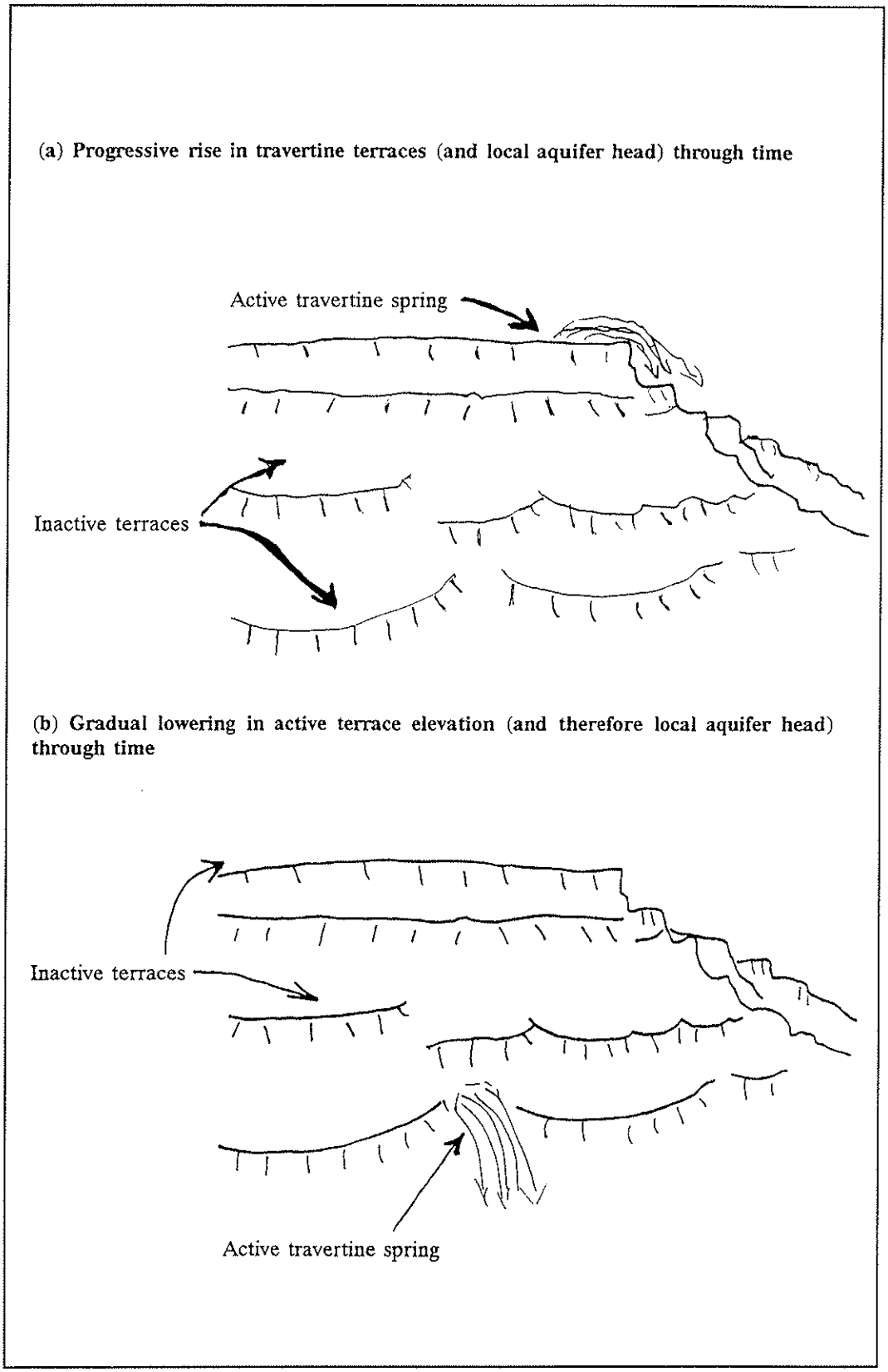


Figure 2 Active and abandoned travertine terraces as evidence of local piezometric history

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buried timbers subsided into the till penecontemporaneously with the death of the tree, when an early period of vigorous groundwater discharge led to the temporary establishment of quicksand conditions. Peat accumulation and humification were intimately linked to variations in spring flows. Radiocarbon dates help to relate these variations to regional palaeohydrogeology, in particular to Holocene water- table fluctuations, which reflect changes in recharge rates (a function of climatic change) and sea level (Younger and McHugh, 1995).

Diagenetic features associated with the water table (hardpans and groundwater gleys) were mentioned above (Section 4). Frequently, the field relations of the soils or sediments hosting such features suggest proximity to a discharge area. In these cases, the locations and elevations of former discharge areas can be mapped.

In karst terrains, certain tube forms characteristic of "resurgences" (in which groundwater rises to a discharge area; Ford and Williams, 1989), can be identified by careful speleological surveying. Such relict resurgences are described by Younger and Stunell (1995) from the Fell Sandstone "pseudokarst" terrain in northern England. However, in the absence of associated chemical or clastic sediments, such features can be difficult to date.

Former coastlines are occasionally recognised in the geological record (especially in the Quaternary). As the base level for all continental drainage, sea-level exerts a fundamental influence on the piezometry of aquifers which are hydraulically connected to the sea. Thus former coastlines of known age which cross the outcrop of permeable strata can readily be viewed as former groundwater discharge areas. For instance, during the last interglacial (Ipswichian), mean sea-level in northwestern Europe was 3 to 5 m higher than at present, and partially buried cliffs and wave-cut platforms dating from this period may be traced across the outcrops of major British aquifers, ie the Chalk (Yorkshire and Lincolnshire) and the St Bees Sandstone (Cumbria). Where the continental land mass has been isostatically stable over long periods of time, the elevations of such relict coastlines might be easily related to former groundwater flow regimes. The elevation of a relict coastline can often be ambiguous in northern latitudes, however, where raised beaches record substantial post-glacial isostatic uplift.

Notwithstanding such problems, sea-level curves for the Holocene have been derived for many sites around the world. While these must be interpreted cautiously (Catt, 1988), several workers have found them to be very useful when reconstructing aquifer histories (e.g. Hiscock and Lloyd, 1992; Younger and McHugh, 1995).

Former positions of lake shores are often conspicuous. Where a particular lake is hydraulically connected to an aquifer, dated former lake levels can provide excellent evidence of former groundwater discharge. However, smaller lakes in closed basins may have withdrawn relatively little water from the aquifer (by evaporation), and substantial groundwater discharge may be restricted to a larger lake (in an open basin, feeding a river) at a lower elevation. Some of the intricacies of groundwater-lake interactions are discussed by Winter and Woo (1990); interpretation of former lake-groundwater systems is not feasible if these intricacies are not considered.

Almendinger (1994) recently applied steady-state groundwater models to determine the water budget around 7000 BP for a number of closed-basin lakes in Minnesota, which are

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all hydraulically connected to the same sandy aquifer. As overland flow is negligible in the area studied, the water budget for each lake can be simplified to the difference between groundwater inflow and the precipitation-evaporation balance for the lake surface. Given former lake levels (2.7 to 4.3 m lower than at present), and a hydraulic conductivity distribution for the area obtained by calibration against modern conditions (ie placing faith in the estimates of present-day recharge), recharge for the period around 7000 BP was manipulated until the model reproduced the former lake levels.

Valley-train sand and gravel deposits are widespread in Europe. In most cases, the lowest terraces are the youngest, and dissected terraces deposited in earlier times flank the valley sides (Catt, 1988). Interbedded organic sediments often allow such terraces to be dated. Many such terraces are thin, and therefore a rough estimate of groundwater level is often available without further investigation. However, groundwater levels during deposition of such sand and gravel deposits usually corresponds very closely to the elevation of major channels which served as groundwater discharge foci. Furthermore (as mentioned in Section 4 above) hardpans formed on the water table are also commonly found in such deposits. It should therefore be possible in many cases to find fairly accurate, dateable, former groundwater levels in such deposits.

6. SYSTEM VARIABLES: PALAEOHEADS AND AQUIFER PARAMETERS

Features which lend themselves to determination of palaeohead include travertines, sand cones, hardpans, groundwater gleys, relict karst resurgences, lake and sea shore-lines and river terraces. If the elevations of such features are measured, and their times of formation determined by dating, then it is easy to calculate the "palaeohead" values which existed in the aquifer at specific times in the past, at the specific locations where these features occur. "Spot" values of palaeohead determined in this manner can be used to constrain mathematical models of groundwater flow which will yield estimates of head at other positions in the aquifer, provided robust estimates of palaeo-recharge are available and that the positions of former aquifer boundaries can be established. This modelling approach has been adopted by Almendinger (1994) and Younger and McHugh (1995).

Palaeohead values are particularly easy to determine in areas with geologically young deposits, which have experienced little or no recent tectonic activity, and where the bedding is horizontal or very gently dipping. Areas with varied Quaternary cover are particularly likely to yield palaeoheads. In such settings, it should be possible to express palaeoheads in metres relative to the current topographic mapping datum for the area (e.g. Ordnance Datum Newlyn in the UK). Where older deposits are investigated, techniques of palinspastic reconstruction must be used (to remove the geometrical distortions introduced by structural deformation) prior to determination of elevations of palaeohead features; in this case, an arbitrary datum should be chosen, and palaeoheads expressed in metres relative to that datum. Ideally, the arbitrary datum should be set at the elevation of the base level drainage control (former sea level, or former lake level etc); if a base level drainage feature cannot be identified, then the datum should be set equal to the elevation of that palaeohead feature which occupies the lowest relative position in the sequence after palinspastic reconstruction.

Aquifer parameters in former times may be difficult to determine. Where the aquifer of

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interest remains saturated, it may be justifiable in a given case to assume that hydraulic conductivity and storativity have remained constant over the period of analysis (e.g. Almendinger, 1994; Younger and McHugh, 1995), and therefore to use values derived from modern tests or model calibrations. Hydraulic conductivity may remain approximately constant over large time periods in a few situations (e.g. clean quartz sandstones which are recharged solely by rainfall), and for any aquifer, the assumption is likely to be most reasonable where relatively short time periods are analysed. Thus in carbonate aquifers, hydraulic conductivity can probably not be assumed constant if the period of analysis exceeds a century or more (possibly much less in some cases). This question is one of the key issues addressed by the GRACE project, and is therefore pursued no further at this point.

Where a granular aquifer can be shown to have become cemented over a given time period, it should be possible estimate former hydraulic conductivity values by calculating the increase in permeability associated with rising porosity, if proportions of the cement were to be gradually stripped away (Younger, 1992b).

Estimating the saturated hydraulic conductivity and storativity of strata which are currently dewatered is more problematic. It may be possible to estimate the aquifer properties of a fractured medium using the cubic law of Snow (1968). For granular media, it may be possible to estimate aquifer properties from grain-size analyses (Uma *et al.*, 1989; Fetter, 1994; Younger and McHugh, 1995), or by lab permeametry (Younger, 1992b). It must be noted that these estimation techniques are not generally considered to yield very accurate results. But even if we accept the estimates obtained uncritically, the results relate to **present** aquifer properties; we still require estimates of how these relate to aquifer properties in earlier times. The usual recourse to problems of this nature is to rely on heuristic knowledge and subjective judgement. While not entirely satisfactory, there is no obvious alternative at the present time.

7. CONCLUSION

Unravelling the evolution and past dynamics of aquifer systems is not a trivial exercise. There are numerous analytical methods which can provide evidence of palaeohydrogeological processes. No single method is sufficient in itself to establish an aquifer history. Therefore any palaeohydrogeological study needs to consider as many types of evidence as possible and to seek a consensual interpretation which is consistent with all the main lines of evidence.

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5

Palaeohydrology and archaeology with special reference to the Middle Trent

A. G. Brown
Department of Geography, University of Exeter

Abstract

Archaeology, as a discipline, has long had a palaeohydrological interest. This has stemmed from archaeological questions concerning the water supply to ancient sites, the management of water resources and the benefit and disbenefits of floodplains as foci for human settlement and transport. With structures such as aqueducts, mills and bridges palaeohydrological work may also be essential in order to explain the functional significance of a site. This paper summarises recent work on the Middle Trent carried out in order to evaluate the environmental context of three unique Medieval bridges buried within the floodplain and excavated in 1994.

The Middle Trent has over the last thousand years crossed the threshold from an unstable wandering/braided channel to a single fixed channel. The stratigraphy of the Hemington reach of the river is dominated by low angle gravel units and shallow channels. Dating has been provided by radiocarbon and dendro-dating of logs and timbers and by archaeological finds including, mills, fish weirs, anchor stones and bridges. In 1994 aggregate extraction in the Hemington reach led to the discovery of three medieval bridges. The stratigraphy dating and archaeology is being used together in order to reconstruct the geomorphology and hydrology of this reach from the Medieval climatic optimum to the present. In this paper the palaeohydrological aspects of the work will be emphasised.

It is suggested that the peculiarities of the Middle Trent catchment, possibly combined with poor channel management, have made it particularly sensitive to hydrological change over the last millennium.

1. INTRODUCTION

This brief paper has two aims; firstly to make the case that palaeohydrology can be of value to archaeologists, and in turn archaeology can be of value to palaeohydrology and secondly to provide a brief interim summary of the palaeohydrological aspects of the work on the Medieval Bridges of Hemington in the Middle Trent valley, England.

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A traditional theme in archaeology has been documenting the affects of environmental changes on human societies. Some archaeologists have therefore long had an interest in the quantity and quality of Prehistoric and Historic riverflow, as a proxy for climate change and because of its close relationship to agricultural productivity. Back in the 1960s Sir Mortimer Wheeler in the foreword to Raikes (1967) prefigured palaeohydrology when he bemoaned "... established belief in recurrent 'change of climate', the imprecise usage of terms such as 'wetter', 'drier', 'warmer', 'more genial': 'wetter' etc. than what?". More recent archaeological studies have continued to evaluate the water supply to ancient sites and farms in the now arid-zone. Two examples are the work by Barker and others (Barker and Jones, 1982; Mattingley, 1995) in Tripolitania and Isere at Petra (Isere, in press). A second palaeohydrological question concerns the interpretation of structures. It has always been remarkable that the Romans seemed to construct surprisingly large and solid viaducts over what today are relatively small rivers even when in flood. It seems doubtful if this can entirely be put down to over-engineering given the tight financial constraints which frequently existed. As these examples show in order to integrate function and structure, or site, palaeohydrological work may be useful. This point will be reinforced by a brief interim summary of the work on the Middle River Trent at Hemington.

2. THE MIDDLE TRENT AND THE HEMINGTON REACH

The Middle Trent has a tremendous wealth of archaeological remains all intimately connected with floodplain processes of deposition and erosion. This is particularly true of the reach between the Derwent junction and the Soar junction in which Hemington is situated (Figure 1). The reach has an inset Holocene floodplain surface which is bounded by gravels forming two terrace levels, and it is floored by gravels. Recent radiocarbon dating of the sub-alluvial gravel indicates that they are of Late Glacial age (Younger Dryas) and were deposited between 11,7000 BP (uncal.) and 10,500 BP (uncal.). The gravels are predominantly horizontally bedded with some shallow cross-bedding and numerous cryogenic features (Figure 2). At the top of the Lateglacial gravel there is an unconformity with Medieval gravels which are similar in grading and structure. Work over many years by C. Salisbury has revealed a complex pattern of palaeochannels (Salisbury, 1992) mostly of Medieval age which have shifted about, and occasionally across an older Neolithic meander core. Whatever the earlier channel state, by the 9th century the river was a highly active gravel bedded system with unstable channels and a tendency to avulse. In this reach archaeological discoveries have included a Norman Mills (Clay, 1992), many basket/hurdle-like fish weirs (Losco-Bradley and Salisbury, 1988), anchor stones (unique to Hemington) and three buried bridges. The bridges are:

1) 11th century caisson bridge
2) early 13th century pile construction bridge
3) mid 13th century wood and stone-pier bridge

The 11th century bridge (Plate 1) is fine example of Anglo-Saxon carpentry but it seems to have failed due to scour between the caissons with one caisson pivoting into the scour hole. Only two caissons were found despite excavation to the north of the site and the stratigraphy suggests that these were the only caissons although they probably had ramps on piles each side. The other two bridges are on a slightly different alignments and are approximately twice as long. In order to investigate the river bed conditions both before

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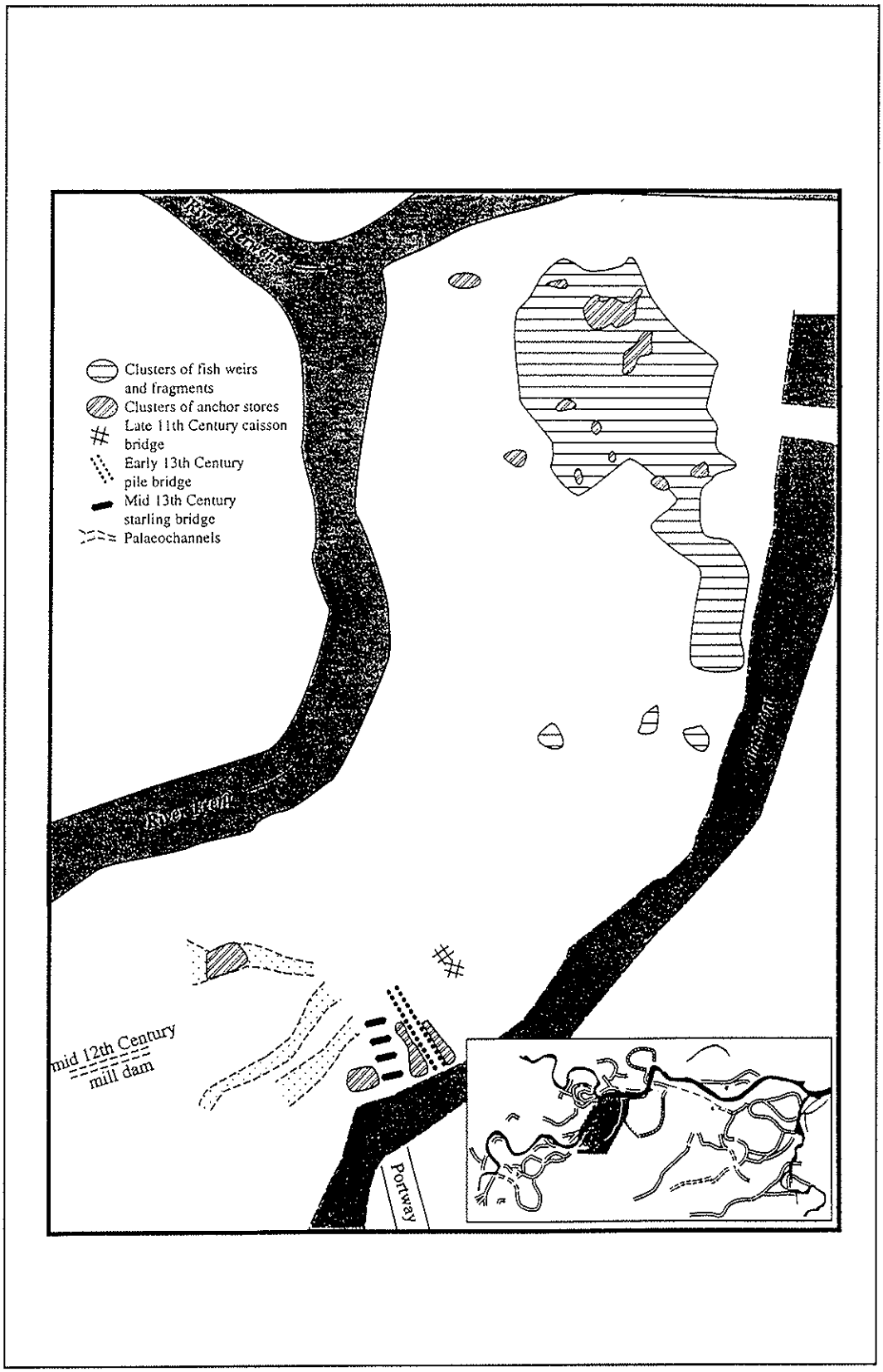


Figure 1 The Hemington reach of the Middle Trent

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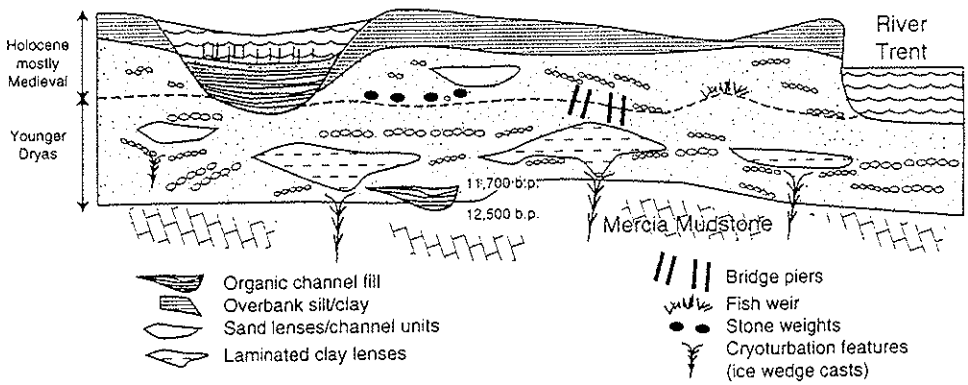


Figure 2 A generalised diagram of the Hemington pit. Largely taken from the work of C. Salisbury (1992; pers. comm.).

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Plate 1 *The northerly caisson of the 11th century bridge under excavation by the Leicester Archaeological Field Unit*



and during the event over 30 detailed stratigraphic sections have been used. The stratigraphy surrounding the 11th century caissons is alternating thin beds of clast and matrix supported gravels each truncated leaving remnants in zones protected from the main force of the flow. Hydraulic conditions are illustrated by scour pool formation. The maximum depth of a scour pool is controlled by the bridge pier size and geometry, sediment size and sediment grading of the bed (Melville and Sutherland, 1988). Using Melville and Sutherland's (1988) method the maximum scour depth of the bridge can be estimated. At the 11th century bridge this was not reached as scour between the caissons is only c. 1.8 m whereas the maximum scour could have been in well in excess of this. This suggests two possibilities; first the conditions were those of clear water-scour with initial armouring of the bed, secondly failure of the bridge occurred before the maximum scour could occur. The premature failure of the bridge was almost certainly caused by the accumulation of woody debris around the caissons increasing the obstruction to the flow and the upstream head. Woody debris was found around the caissons during the excavations, and this phenomena is known to have been, and still is, a particular problem on the Trent. The problem of pier scour was recognised by the builders of the mid 13th century bridge who constructed a baffle in front of one of the piers. Preliminary palaeohydraulic work has been undertaken using the largest pebble sizes moved and the smallest believed not to have moved. Standard palaeohydraulic methods have been applied (Maizels, 1983) with Shields function and Du Boys equation used to estimate critical flow depth, resistance estimated using the Darcy-Weisbach equation and velocity finally derived using the Manning equation. A check is made that the calculated Froude number is realistic. This procedure gives an estimate of 4-6 $m^3 s^{-1}$; the reason for the large range is a gap between the two size ranges and the power relationship between velocity and size-selective particle entrainment. Using EDM survey of the stratigraphy and the structures

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estimates can be made of the formative bankfull discharge of the channels across which the bridges were constructed. Two methods have been used, the standard slope/area method and HEC II water surface profiling (Eagle Point, 1993). Due to the uncertainty in the input data, especially the energy slope and the channel roughness it is only possible to suggest a most probable discharge range. For the 11th century bridge this is 50-70 m^3 s^{-1} whilst for the 13th century channels this is 120-170 m^3 s^{-1}. The present bankfull of the Trent at this reach is 200 m^3 s^{-1}.

2.1 Palaeohydrology and Site Context

Climatically-driven hydrological change of the magnitude suggested above is too great to be caused by Holocene climate change and almost certainly reflects the changing channel pattern of the floodplain. Both the sedimentology and archaeology suggest significant channel change in the 9th to 13th centuries. Using both archaeological and geomorphological data a model has been proposed of the channel change in this reach (Figure 3). In the 9th century a bi-channel system is suggested which has its origins in a braided system with a larger western arm joining the Derwent and a smaller eastern arm cutting across a large gravel bar to rejoin the main channel downstream of the junction. The caisson bridge is constructed across the smaller eastern arm possibly with a causeway across the floodplain to a ferry, ford or perhaps another bridge across the northern arm. The flood that destroys the caisson bridge diverts more flow down the eastern arm and this leads to the eastern arm taking most of the flow whilst the western arm becomes less competent. There is, however, the intriguing possibility that this shift was not entirely a natural event. Since sometime in the early 12th century a mill was constructed across the main channel upstream of the bridge locations (Clay, 1992). The mill used the easterly channel as an overflow and it is believed that it was destroyed in the Great Flood of 1140 AD. This flood did considerable damage throughout the Trent system and it was probably at least as large as the 1795 flood. One reason for suggesting this is that it is the only flood recorded prior to 1795 to have breached the Spaldford bank which prevented the Trent from flooding into the Witham-Fens system (Potter, 1964, Padley, 1882). The 1795 flood has been estimated at 1,400 m^3 s^{-1} (Potter, 1964). Using the ranking of historical floods on the Trent this would suggest a return period of *c.* 1:400-1:800 years, however, floods of a very similar magnitude occurred in 1346, 1403, 1684, 1875 and 1947 (Potter, 1964). There is some evidence here that of an absolute maximum to Late Holocene floods of the Trent and a 200 year flood cycle, although with such an imperfect and short record (only X4 the cycle) this remains difficult to prove. Hydrological cycles of similar magnitudes have been shown from a variety of proxy data sources including ombrogenous bogs (Barber *et al.*, 1994). There is, however, no doubt that this reach during the so-called Medieval Warm Period (Hughes and Diaz, 1994) was still subject to large floods similar in magnitude to those to be experienced during The Little Ice Age.

3. CONCLUSIONS

Thus, fluvial activity has to a significant extent, along with social and political factors, controlled the formation and destruction of the archaeological record of the Middle Trent and in doing so it provides us with a unique source of palaeohydrological data. Palaeohydrological analysis may be essential to explain the dimensions, function and history of some structures, particularly bridges as is the case at Hemington. The

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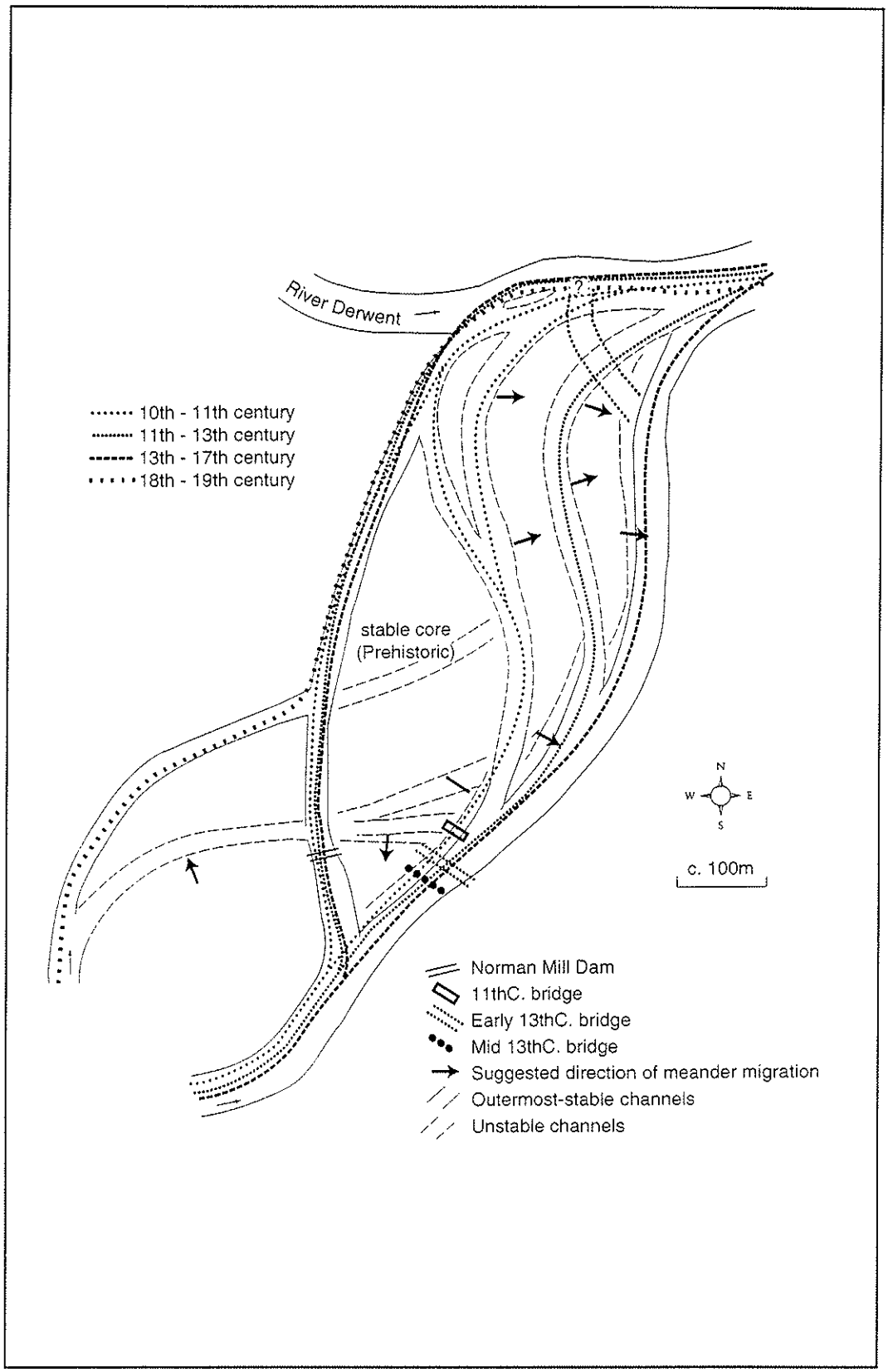


Figure 3 A schematic geomorphological model of channel change in the Hemington reach from the 9th century AD to the present.

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archaeology of the Middle Trent is greatly influenced by its mobile (braided) state - and more specifically its Late Medieval archaeology has been patterned by the transition of the Trent from that braided state through an anastomosing state to a single-channel meandering state. It is also clear that the twelfth century was not free from large floods, and it is possible that the so-called Medieval Warm Period was one of greater continentality in Eastern England (with warmer summers).

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6

Building the foundation for long-term hydrological research - the role of the database

J. Branson
GeoData Institute, University of Southampton

Abstract

The data collected during palaeohydrological studies are a valuable resource which can often be used in applications outside the context for which they were originally collected. Use of the data by a wide group of potential users (representing researchers, engineers, hydrologists, students and others) is inhibited however by the lack of data which are available in the public domain. Data access can be improved through the compilation of data into a centralised database which can bring together data from the different disciplines which comprise palaeohydrology into a secure, standardised structure. Far from being simply a filing system a database can facilitate the creative analysis of data and can contribute both to the study of long-term hydrological change and provide a resource for the study of hydrological change in the long term. Such a database should be seen as part of a family of environmental databases, with ability to cross-reference to each other and potentially to maintain elements of data sharing.

1. INTRODUCTION

1.1 The Value of Palaeohydrological Data

The preceding chapters of this volume have described how the study of individual aspects of environmental research can contribute to the knowledge of hydrological change in the (usually Holocene) past, and how these changes have impacted on the physical and human environment. The data collected during these studies, encompassing groundwater levels, geomorphological features, palaeoecology, palaeohydrogeology, documentary evidence and peat bogs are valuable sources of information that are used to build up a picture of the hydrology at a particular place at a particular point in time. However, it is necessary to recognise that palaeohydrological data can also provide a valuable resource in the context of a wide range of other environmental studies and applications relating to the past, present and future changes in hydrology and the landscape. Some examples of this wider dimension of palaeohydrological data are discussed below.

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1.1.1 Analysis of environmental changes in the geological past

Long-term hydrologic data are an essential resource base for determining how streamflow, groundwater levels, sediment yields, and soil moisture varied in the remote geological past when the physical, climatic and ecological conditions were different from the present-day environment (Baker, 1983). Similarly, palaeohydrological data from the recent past can provide information to establish the role of rare, high magnitude events (such as catastrophic floods or debris flows) as agents of landscape form (Baker, 1983).

1.1.2 Landscape evolution

Past rates and magnitudes of palaeohydrological change can act as a context for examining present rates. An established time series of such indicators can help provide a perspective on the degree of geomorphological stability and sensitivity to change and landscape evolution. Historical data can be used to indicate whether particular reaches of a river have been stable or unstable over a given timescale. In this respect, Leeks, Lewin and Newson (1988) stress that it is important to view individual rivers as systems with a history, and that this history should be taken into consideration when designing schemes which impact upon the river. Information of past and present sediments, bank erosion rates, flood frequency and discharge obtained from studies of maps, documentary evidence, sedimentary sequences, landscape elements or long gauging records should therefore be used by engineers and geomorphologists when designing flood protection, maintenance or other schemes. If these data are not used then problems may result, as highlighted by Leeks, Lewin and Newson (1988) with regard to a flood protection scheme that was designed with limited reference to the history of the river. It was argued that the problems would have been avoided if note had been taken of the historical evolution of the river.

1.1.3 Study of future hydrological changes

A number of large and small-scale studies with ever-increasing data requirements are attempting to predict the changes that will occur in the hydrological cycle under conditions of future global warming. This subject has become increasingly important to the general public in the light of recent periods of low rainfall and catastrophic flooding, and interest in environmental change is now accompanied by an acute concern of the debilitating effects of drought and flood.

In trying to predict future changes, data from the instrumental record are most often used, however, as been evidenced in the preceding chapters of this volume instrumental records are limited in extent, and in addition, it has been argued that data from the last millennium does not adequately describe the range of potential future changes (e.g. PAGES, 1995). Hydrological and related data from periods such as the Holocene warm optimum could therefore be used to extend the available data resource and as a scenario for what may occur under future conditions of climate warming, and knowledge of river flow, groundwater and lake levels from previous periods can enable current events to be put into a wider context. An advantage of this approach is that the prediction of future changes are probably more reliable if a historical perspective is used rather than relying solely on contemporary knowledge (Hooke and Redmond, 1989).

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1.1.4 Water supply, flood protection and waste disposal schemes

Schemes for water supply and flood protection are designed to accommodate sequences of events drawn or extrapolated from the past records. Normally the calculation of design parameters is based on instrumental records of only 10-50 year duration. It is realised that the confidence in return interval calculation is sensitive to the duration of record and the stopping rules. Such uncertainty and the resulting factors of safety in engineering design may be reduced if palaeohydrological data are used to reconstruct long-time series of parameters such as discharge, flood frequency and groundwater level.

As a result of the present scattered nature of data on past events there is a challenge to bring these data together to provide a uniform data source for water resource planners and engineers. Indeed, the value of palaeohydrological and other data for use in flood analysis was emphasised by the studies following the 1993 Mississippi flood in that 'policy decisions are being made in a data vacuum. Yet we are now in an era when the ability to collect and use field data has been greatly augmented by satellite and computer based techniques' (Association of State Floodplain Managers, quoted in Interagency Floodplain Management Review Committee, 1994; p. 155). Baker and Ely (1990) and Baker *et al.* (1990), amongst others, have undertaken a number of studies that have used palaeo-flood data as a tool in schemes such as flood-hazard zonation and reservoir design. Similarly, studies of isotope palaeohydrology have also been used in conjunction with predictive models to determine the future stability of parameters such as groundwater recharge in the region of sites of potential waste repositories.

1.2 Current Availability of Palaeohydrological Data

The acknowledged value of palaeohydrological data to researchers, engineers and hydrologists is mediated by the lack of access to such data, for a number of reasons. For example, data are usually not put into the public domain following completion of a project or a programme of monitoring, and are thus not accessible to interested users outside the groups which collected them. This apparent limited availability of data is confirmed by the data collectors themselves. A recent survey of scientists who have undertaken palaeohydrological research indicated that 63% of respondents retained their data on original paper listing sheets and the remainder held data in computer database or spreadsheet formats only accessible to themselves.

Data are sometimes available within publications but are usually presented in summary form, without detailed supporting information summarising procedures of data collection and calculation, and as a result usually have limited, contextual value for use within other studies. Therefore, the entire datasets are not widely available to others who may be interested in them. Frequently therefore, it is not that there is a distinct lack of data, rather a lack of data availability. Related to this problem, and perhaps of wider concern, is the potential for data loss when personnel change their careers or organisations change their remit. These materials may be significant for historic studies or form part of a longer time series of data and should therefore be safeguarded. This situation is not unique to palaeohydrological data but is repeated in many other disciplines (e.g. Barry, 1995; Barry, Heginbottom and Brown, 1995; Rapley, 1996).

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2. SOLUTIONS TO THE DATA SUPPLY PROBLEM

2.1 A Framework for Data Sharing

Palaeohydrological science, along with many other disciplines faces a challenge to safeguard its resource of data and information for present and future generations to utilise, and a solution may be to create a central archive of data. To meet this challenge requires a three-stage process, involving (1) identification of datasets of particular value or interest, which includes highlighting of any datasets that may be at risk of being 'lost', (2) requisition of the datasets selected and (3) compilation and consolidation of the datasets into a coherent structure. Whilst described as a sequence these stages run somewhat in parallel and if they are to be effective must be a continued process.

The first stage is best addressed by an inventory of researchers, groups and institutions which hold relevant datasets. These inventories can then be used to prioritise data rescue and acquisition efforts (e.g. Barry, Heginbottom and Brown, 1995) which form the basis of the Stage (2) requisition activity. Once data collection has commenced within Stage (3) it is important to devise a framework into which the data can be collated and accessed, and one of the most efficient ways of achieving this is by construction of a database. A database is simply a collection of data; hydrological yearbooks and bibliographies represent databases, for example, but modern databases are generally computerised and have many advantages over their paper counterparts in that they can be easily updated, queried, duplicated and distributed.

2.2 Hydrological Data Archives

The collection of palaeohydrological data has many parallels with the production of archives of contemporary hydrological parameters which have been under development for a number of years. In the 1960's Leopold appreciated the need for long-term, high quality standardised datasets as a tool for the study of hydrological change in stating that 'those of us who seek to explain the variations in hydrologic phenomena ... are painfully aware of the lack of adequate data' (Leopold, 1962; p.5). This recognition led to one of the earliest attempts to collate a resource of hydrological data from individuals for more widespread use, known as the Vigil network (e.g. Leopold, 1962; Emmett, 1965; Osterkamp, Emmett and Leopold, 1991). The Vigil project encourages hydrologists to collect a standard series of baseline data (comprising parameters such as channel cross section) from network drainage basins over a number of years. The data were originally archived in paper format in repositories in both the USA and Sweden to ensure security of the data holdings and widespread access to data (Emmett and Hadley, 1968). An aim of the Vigil project is to afford a nucleus for international cooperation in hydrology by providing a data resource in a standard format for future generations of scientists to use.

By the 1980's, despite efforts such as the Vigil network, access to data throughout many of the environmental sciences remained limited, and Hopke and Massart (1986; p. 193) stated that 'considering the time, effort and expense that generally goes into sampling and analysis, it is an unfortunate loss to the scientific community that those data are not readily available in a known format with sufficient information to make them useful to others' (see also Saunders, Shields and Taylor, 1995). In stating this, Hopke and Massart underlined the basic requirements for a data and information system, namely that data

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should be readily accessible and include sufficient information to make them useful to others. These two components provide the foundations on which the development of a database (in this case palaeohydrological) should be based.

2.3 Recent Palaeo-database Efforts

The value of a palaeo-data, the lack of access to it, and the need to provide information about data is now being recognised within the palaeosciences, and an increasing number of projects have been established during the 1990's to provide palaeodata within the scientific community. Many of these projects are under the umbrella of the World Data Center-A for palaeoclimatology, which is a central repository for a large volume of palaeo-data, and the Past Global Changes (PAGES) group on data and information (e.g. PAGES, 1995; Pilcher, 1996). Similarly, international programmes such as the International Geosphere Biosphere Project (IGBP) and the Global Terrestrial Observing System (GTOS) have adopted detailed data policies which require a commitment to the preservation of data, data sharing and the establishment of data standards (e.g. Townshend, 1996).

This increase in the number and diversity of databases is timely in that many grant bodies now require that data collected in the course of funded projects should be archived in the public domain within a given timescale. Additionally, due to the mobility of personnel and as institutions change their remit there is a concern that large datasets may be lost and thus there is a recognised need for these data to be held within a central archive.

The creation of data archives is therefore an important process in that it ensures continuing security and accessibility of important data (subject to a number of constraints discussed below). However, it is important to appreciate that data archives do not just have to represent inert data storage devises imitating the traditional box file, but can also provide a framework for highly sophisticated data search and analysis. Some of the roles that a database can fulfil are discussed in the section below.

3. ROLES WHICH A DATABASE CAN FULFIL

There are two fundamental reasons to compile datasets into databases or archives, namely to facilitate the preservation and free access of data. In promoting these two goals a database fulfils three main roles, enabling the *organisation*, *facilitation* and *association* of data. These roles are discussed in further detail below and in Branson, Clark and Gregory (1995) and Branson, Gregory and Clark (1996).

3.1 Data Organisation

In terms of organisation a database can consolidate datasets from a variety of sources into a centralised system (or within distributed systems linked together), and in doing so can increase data security and reduce vulnerability to loss (providing that data are backed-up frequently and the storage medium is kept current).

An important aspect of this organisation, particularly where a number of original storage formats, ranging from field notebooks to a variety of software packages, are involved, is the standardisation of data from disparate sources into a common format, thus making it

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simple both to use different datasets within the new centralised system and to compare between datasets collected by different groups. This consolidation of data is a difficult and challenging task and can only be achieved effectively by the establishment of efficient data transfer protocols between the database compiler and the data owners/collectors. Potential problems arise in that data obtained by different researchers at different times could have inconsistencies in attribute definition and spatial accuracy, and it is important that these inconsistencies are corrected and/or noted within the database.

If the problems of data compilation can be overcome, then the efficient organisation of data (commonly achieved using relational database management systems) makes it possible to provide both raw and processed data to the database user. This allows reanalysis and reinterpretation where analytical techniques are modified or new techniques developed. A further advantage of data organisation is that simply by bringing a number of datasets together into one location it is possible to identify gaps in data availability and perhaps steer new research efforts towards areas where at present no data exist.

3.2 Data Facilitation

Beyond the organisational role databases can fulfil more complex and arguably more useful roles that initially rely on the efficient organisation and manipulation of the data. The facilitating role describes how the database is used to gain access to the data and comprises two parts; i) the identification of datasets of interest and ii) the retrieval of data. In a paper database (a hydrological yearbook, for example) an index provides the facilitating role by grouping the information into categories and then indicating where (by page number) individual items of data can be retrieved. Computerisation has provided additional flexibility to data facilitation, allowing complex queries to be constructed that select data that conform to specific criteria - such as a particular timeframe, location or datatype - and enabling selected data to be output in an appropriate format for the end user. Networks, such as the Internet, with sophisticated search facilities potentially allow data to be identified and accessed immediately at minimal cost worldwide and thus make data available to a much larger audience than if the data were available solely in paper format held in a limited number of libraries.

To assist in the facilitating role of the database it is important that a high level of metadata is maintained. Metadata are 'data about data' and provide background information about the context in which the data were collected, the techniques used and personnel involved, and also indicates whether data were converted from their original format when entered into the database. The metadata should be sufficiently detailed so that the data can be used without the user needing to contact the data author for addition information. In a multidisciplinary dataset it is particularly important that a high degree of metadata are provided, so that users are aware of the context in which the data were collected and analysed. To this end many systems incorporate dictionaries of standard terminology for their particular subject (e.g. Saunders, Shields and Taylor, 1995) ; this should prevent users from exploiting the datasets in ways that are not appropriate. To enable the investigation of the data, which forms the third main role of the database (see below), a database can either contain routines for analysing the data or presents the data in formats so that they can be easily imported into time-series or spreadsheet software.

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3.3 Data Association

Whilst the organisation and facilitation of data are valuable undertakings in their own right it is important that databasing efforts do not stop here, and it is encouraged that projects go one step further and analyse the data in their new form. In this respect Branson, Clark and Gregory (1995) use a banking analogy drawing a comparison between a data *bank* and a data *investment*, the former ensuring security and integrity of the data but the later enables value to be added to the data. Some aspects of value-add which enable individual datasets to be extended in space, time and attribute domain are discussed below.

Given the time- and labour-intensive character of palaeohydrological studies most individuals or research groups investigate a limited number of sites, and in analysing the data it may not be evident whether the trends seen are a function of local, regional or global influences. If a number of datasets from different locations and timescales are combined, however, it should be possible to put individual studies into a wider-context - something that is usually done in the context of a literature review but a database can provide a more comprehensive and more easily accessible resource.

If this concept is extended then it is evident that by combining records it may be possible to identify patterns in data, relate the changes in one phenomenon to changes in another, offer insights into causal relationships and identify trends and event frequency that cannot be identified on the basis of single studies (Scientific Assessment and Strategy Team, 1994). By combining data from individual sites it may be possible to extrapolate to determine a regional or continental picture of change, and ultimately by combining regional and continental studies, a global picture of change may be possible. Similar approaches are used widely in other palaeosciences, for example dendrochronology, to indicate spatial cross-correlations of events identified or correspondence of interpreted environmental conditions. Palaeohydrology has a distinct advantage in this respect in that it comprises a number of disciplines (e.g. geomorphology, hydrology, ecology, archaeology, geology, hydrogeology, history and see Gregory, this volume). Individual studies are often concerned with only one data type, but if different data types are brought together then it is possible to compare the responses of the different elements to a particular event and to study the hydrological landscape as a whole. For example, with a number of data sources available for a particular flood it may be possible to identify the climatic and other antecedent conditions that forced the occurrence of the flood, then determine how the discharges of the river changed during the flood wave, the effect of the flood on the human environment and observe how the channel form reacted at various timescales after the flood.

Thus, the real strength of large databases is that through the analysis of the aggregate datasets it should be possible to recognise patterns and timescales of change beyond the boundaries of individual datasets. Clark (e.g. Clark, 1995) terms this form of investigation for patterns and coincidences 'data mining' and Openshaw (1994) suggests that the search for patterns within data requires a tri-space procedure where data can be searched for in patterns which incorporate time, space and attribute dimensions. This sort of analysis lends itself to incorporation within a Geographical Information System (GIS) and thus it is important that the database is configured such that the data can be linked directly or indirectly with GIS software.

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That the use of consolidated datasets provide an important element of palaeohydrological analysis is evidenced by a number of papers in a new volume (Branson, Brown and Gregory, 1996), among others, which have used data compiled from a number of sources to identify trends in sediment yield (Walling, 1996), clustering of flood occurrence (Benito, Machado and Perez-Gonzalez, 1996; Enzel *et al.*, 1996; Kale *et al.*, 1996) or similar chronologies of change in difference regions (Thomas and Thorp, 1996; Rumsby and Macklin, 1996).

4. ISSUES FOR DATABASE DEVELOPMENT

Many of the procedures involved in the design and development of data and information systems for environmental and palaeo-science have been outlined in a number of publications (e.g. Branson, Clark and Gregory, 1995; Branson, Gregory and Clark, 1996; PAGES, 1995; Giles, 1995), and so therefore will not be repeated here. There are a number of issues that should be addressed during the design process however, and these are briefly discussed below, with particular reference to palaeohydrological databases.

4.1 Data Guidelines

Section 3.1 emphasised that it is advisable that common standards of data storage are adhered to, to ensure that individual datasets within one database are compatible. Taking this one step further, if standards were to be established throughout the database community then it should make it possible to exchange data between databases developed by different groups.

Recently, attempts have been made to define standards for particular data types. For example, PAGES have produced a series of common data management guidelines for palaeo-database projects (PAGES, 1995). In these guidelines PAGES have set out general principles which it is suggested that all palaeo-database efforts should adhere to, i.e. data should be freely distributed and available without restriction, data archived should include both reconstructed and raw data from which reconstructions were derived. These guidelines, and others, also specify the minimum requirements for environmental datasets in general and for particular data types (e.g. tree ring, Fritts (1995); pollen, Grimm (1995); fluvial, Branson (1995); lake level, Harrison (1995), PALE Steering Committee (1993); groundwater, Doorgakant (1995), McKenzie, (1995)). Many of these data sources will be of direct interest and relevance to palaeohydrological analysis.

4.2 Recognition for Data Authors

A database is of little utility if it contains limited amounts of data, but it is acknowledged that individuals have little incentive to contribute their data if no recognition is given for the effort involved in preparing data into a format that can be used by others. To date there is no generally adopted method of citation but there have been a number of proposals. The World Data Center-A for Paleoclimatology has created a data contribution series which has the purpose of giving citation credit for data contributions, ensuring that digital datasets are archived in their complete form, and that subsequent modifications are made available and also to encourage more data to be published (Overpeck, Webb and Anderson, 1996; PAGES, 1995). The number of the data contribution is cited by users of

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the dataset in conjunction with published papers or reports by the data author that discuss and analyse the dataset.

In addition to citation series, a number of journals now include 'data and analysis notes' in which individual databases or datasets are described and details of access to them given (e.g. Hornberger, 1994). This approach has two advantages in that authors obtain a publication and potential users are made aware of the data, and is important where effort has been expended upon creating a dataset that can be used widely, but the dataset is not written up in a scientific publication. The notion of citation of datasets and databasing is also important where academic evaluation utilises citation as a parameter.

4.3 Promoting Data Access

The range of potential users of a palaeohydrological database were discussed in Section 1. For the data to be used effectively by users in these areas it is important that detailed information are provided so they can be easily understood by those who may not be familiar with the techniques or particular element of palaeohydrology. To a great extent this information is provided by the metadata (see above), but can also be provided by careful choice of the mechanisms by which the data are made available to the users. The use of specific technology, such as multimedia software, can be particularly valuable within an educational context where it may not be appropriate to provide only raw data, whilst use of the Internet can allow users to interact with the data and to download datasets of interest at minimal cost. If these forms of technology are used it is possible to provide, in one system, the hydrological time series plus the raw proxy data, the derivation procedures, and some background on the evolution of the physical and social landscape in the context of changes in the water environment in an easily accessible electronic format. Similarly, tools such as PaleoVu, developed by WDC-A provide easy access, browsing and output of data from a number of datasets (e.g. Overpeck, Webb and Anderson, 1996).

4.4 Data Update

Once a data system has been developed it is important that the data collation effort is not simply a one-off procedure with a defined end-date. Data maintenance, management and distribution should be an on-going and active process, in which new data are added and existing data modified in the light of new analysis if the full potential is to be realised. It is also important that individual systems are responsive to the needs of their user communities and can accommodate changes in software or storage formats.

5. CASE STUDY - THE GLOCOPH DATABASE

The Global Continental Palaeohydrological (GLOCOPH) project is an example of the use of a project which has exploited database technology to provide a tool to identify patterns and causes of hydrological changes through the last 20,000 years. The construction and development of the database has been described in Branson, Clark and Gregory (1995) and Branson, Gregory and Clark (1996). The following illustrates how the database project is enabling the organisation, facilitation and association of palaeohydrological data.

The database, developed using the Oracle relational database management system, has a

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number of components; a bibliography of palaeohydrological and related literature, a list of researchers, and palaeohydrology datasets. The data relating to each dataset falls into three categories; (i) metadata, (ii) raw data, comprising the data collected in the field, i.e. channel parameters, sediment size, sedimentological sequences and (iii) the reconstructed values, such as discharge or velocity calculated from the raw data, including details of the equations and models from which the reconstructions were made. Including the raw data within the database makes it possible to re-analyse the data if new models are derived.

At present the majority of sites included in the GLOCOPH database are those which were investigated during the IGBP project 158 'Palaeohydrology of the temperate zone' (e.g. Starkel, Gregory and Thornes, 1991), but current efforts are aimed at obtaining a more global coverage. Thus the GLOCOPH database is achieving the organisation of datasets from different researchers in different parts of the world within a single database.

Facilitation of data in the GLOCOPH database is being achieved through provision of data on WWW pages on the Internet and distributed on disc and hardcopy for those with no access to the Internet. The Internet pages also include resource pages for palaeohydrology with details of data, information about meetings and the bibliography.

6. CONCLUSION

It has been shown that the compilation of datasets into a central database can be of value to rescue data and promote access to them, to facilitate data analysis and the identification of patterns of change. A database can provide a means of preserving and allowing interpersonal, interdisciplinary, intra-national and international data sharing and thus helps exploit the data and provides a tool for research, engineering, hydrology and educational purposes for present-day and future generations of user.

It is suggested that there is no time like the present to attempt to collate and protect palaeohydrological data. Whilst recognising the needs for standardisation and flexible recording that do not tie the data to particular hardware or software, inevitably changes in data models and databasing protocols will call for transfer and translation. These elements are important procedurally but the strongest message must be that the data are the primary assets rather than the details of the IT structures.

As with many other projects of this type, the more data of known standard or quality that a database holds, the greater its functionality. A well configured and populated database becomes a self-sustaining research tool encouraging further data input, archiving and utilisation. Data owners are therefore strongly encouraged to archive their data within a large-scale data project.

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