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Re-construction of historic drought in the Anglian Region (UK) over the period 1798–2010 and the implications for water resources and drought management

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SUMMARY

This study reconstructs droughts during the period 1798–2010 and assesses the consequences for water resource planning, drought management and resilience across the Anglian region (UK). Rain gauge series were extended to cover the period 1798–2010 and used to produce a 213-year daily dataset on a 5 km × 5 km grid matching recent data produced by the UK Met Office. Potential evapotranspiration data was extended using the Thornthwaite equation, based on data from the Central England Temperature series and potential evapotranspiration from the Met Office Rainfall and Evapotranspiration Calculation System. Rainfall and potential evapotranspiration series were input to rainfall-runoff models and flows simulated from 1800–2010. Reservoir simulation using these flows indicates that inclusion of pre-1920 droughts does not reduce yields and actually increases yields at five reservoirs, ranging from 1% to 16.6%, compared with the post-1920 period, the period normally used in reservoir yield calculation and the preparation of Water Resources Management and Drought Plans. Post-1920 droughts define drought intensity at all 5 reservoirs and, with some exceptions, comprise the three worst droughts in the period 1800–2010. Droughts during 1933–36 and 1943–46 are the most severe in the west of the Anglian region, 1989–92 in the north and 1996–98 in the east. 1854–1860 emerges as the period of regionally highest ranked drought severity in the period 1800–1919, but 1893–1907 also features strongly in the west. Contiguous dry winters and summers are a feature of the more severe droughts. Drought periods are consistent with previously reported major drought episodes in England and Wales, with the notable exception of 1801–1816, which emerges as much less severe from this study. The worst hydrological droughts from runoff deficiency analysis do not generally appear critical for reservoirs, emphasising the importance of simulating reservoir response over a long time span and suggesting that individual reservoir storage and infrastructure provide resilience. Despite spatial variability, the more severe droughts are widespread (e.g. 1854–60, 1933–36) and may influence resilience of the larger integrated water resource system that includes river and groundwater sources. Extended sensitivity analysis should be carried out to quantify uncertainty arising from data reconstruction and hydrological modelling, including the choice of model, before inclusion of reservoir yields in Water Resource Management Plans. The 'library' of drought information from this study, paralleled by sensitivity analysis, will be useful during drought for reservoir scenario projection and quantification of the risk of restrictions to supply, such as the effect of a ban on the use of hosepipes; in 'planning mode' for testing the robustness of Drought Plans; and for application to other catchments across the region. Long rainfall and temperature series and recorded river flows are available for extending the approach used here to elsewhere in the UK, Europe and other parts of the world.

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1. Introduction

1.1. Droughts and water supply in the UK

Under the influence of climate, geology, soils, land use and hydrological response, droughts exhibit considerable temporal and spatial diversity which must be taken into account when designing and managing public water supply systems. Detailed knowledge of historic periods of drought is thus fundamental to the specification of source yield and Deployable Output[2] in Water Resource Management Plans (WRMPs), the development of Drought Plans (DPs) and the management of water resources during drought episodes. UK water companies have a legal obligation to produce WRMPs[3] and DPs[4], following detailed guidelines produced by the UK Environment Agency (Environment Agency, 2012a, 2011). WRMPs are produced every 5 years and describe the actions that companies will carry out to ensure the security of water supply over the next 25 years or more. DPs are produced every 3 years and set out how companies will maintain supply during periods of low rainfall whilst minimising potential environmental impacts. Although there are a range of drought definitions (Wilhite and Glantz, 1985) here we focus on hydrological and water resources drought. Hydrological drought results from changes in precipitation, evaporation and storage leading to a deficit in runoff over a specified period and water resources drought from a shortage of water to meet the demands of public supply, industry and the environment due to a combination of hydrological drought and socio-economic factors (Von Christierson et al., 2009).

1.2. Availability of historical data

In the UK, since 1997, the standard method used by the UK Water Industry for deriving the yield of surface water sources has been behavioural simulation, including operational constraints, over a period of historic river flows (Jack and Lambert, 1992; McMahon and Adeloye, 2005). This is in line with Environment Agency guidelines and takes into account the way sources would be operated in severe droughts (Environment Agency, 2012a). Behavioural simulation has been widely used beyond the UK for determining reservoir yield (see for example McMahon et al., 2007b; OWASA, 2013). One of the potential limitations of this approach is the brevity of river flow records (Marsh and Hannaford, 2008) and hence the limited sample of severe droughts. Globally, McMahon et al. (2007a) found that in a subset of 729 unregulated rivers with 25 years or more continuous *monthly* or *annual* data the 90th percentile record length was 65 years, with only six records longer than 100 years. Although the UK has an exceptionally dense river gauging network, record length is still a limiting factor: for a subset 1176 river gauges with 25 years or more *daily* mean flow data, the 90th percentile record length was 54 years with 2 records exceeding 100 years (NRFA, 2014). In the Anglian region most records in catchments from which the main water supply company, Anglian Water, abstracts start around 1960, the exceptions being a cluster of river flow gauges in catchments of the upper R. Nene[5] above Duston (Fig. 2), starting in the late 1930s or early 1940s and the R. Great Ouse at Bedford, starting in 1933, although with limited accuracy before 1959 (NRFA, 2014). To overcome this issue Anglian Water developed mean daily river flow series starting in 1920 to comply with the guidelines' recommendation that behavioural simulation "should use rainfall and other data to model the period back to 1920 if direct river flow or groundwater level records are not available" (see Environment Agency, 2012a). These flow series, starting in 1920, are composed of periods of recorded or naturalised-recorded data and data produced by rainfall-runoff modelling and have been the basis of Anglian Water's reservoir yield assessment for more than 15 years.

The resulting reservoir yields, based on severe droughts in 1921 (Brooks and Glasspoole, 1922), 1933–34 (Glasspoole, 1935), 1943–44, 1976 (Rodda and Marsh, 2011), 1989–92 (Marsh et al., 1994; Bryant et al., 1994) and 1995–97 (Marsh and Turton, 1996), have provided input to supply–demand analysis and company WRMPs (see, for example, Anglian Water, 2014c). However, recent studies have indicated periods in the 19th and early 20th centuries when conditions were equally or more severe (Jones et al., 2006a, 2006b; Cole and Marsh, 2006; Marsh et al., 2007) and reservoir yields were reduced (Wade et al., 2006). These conditions, if repeated, potentially would present considerable challenges for managing water resources (Watts et al., 2012). It is also worth noting that major drought episodes, such as the Long Drought of 1890–1910 in England and Wales (Marsh et al., 2007) could occur again even without climate change.

There is a requirement for consistency between WRMPs and DPs (Environment Agency, 2012a) which has been achieved by using the output from reservoir yield analysis in DPs, e.g. reservoir storage curves which trigger the introduction of restrictions to supply. Consequently, DPs are also based on post-1920 drought evidence and therefore may not provide adequate resilience for water resource management. However, extension of rainfall, evaporation, river flow and reservoir storage over a much longer historic period, i.e. more than 200 years instead of the current 90 years, could reveal more severe droughts for testing the resilience of water resource systems and improving drought planning and management. Watts et al. (2012) point out that such analysis may help to identify water resource development options that would increase resilience to historic climate variability and reduce vulnerability to future climate change.

1.3. Existing studies

There have been several studies reconstructing long climate and hydrological series for UK catchments, although few have utilised the data for water resource assessment. Extensive work has been carried out within the Climatic Research Unit (UK) (CRU, 2014; see also Burt et al., 2015) to produce long term and homogeneous monthly rainfall records for the UK and Ireland. This drew on early work by Tabony, who also constructed series for 15 European countries, including France, Italy, Sweden, Holland, Austria and parts of Germany (Tabony, 1980, 1981; Jones, 1983a). Using the European rainfall data and long temperature records the self calibrating Palmer Drought Severity Index (Wells et al., 2004) was used to assess trends in soil moisture and summer drought since 1750 (Briffa et al., 2009). The UK rainfall series were used by Jones (1983b, 1984) for input to an empirical catchment model (Wright, 1978) to simulate monthly flows for the R. Thames back to 1885, R. Tyne to 1863 and R. Wharfe to 1854, using extended rainfall data and seasonally constant actual evaporation. The same approach was used to extend flow reconstruction back to the 1860s for 15 catchments distributed around the UK and use these data to assess the severity of hydrological drought (Jones and Lister, 1998; Jones et al., 2006a). Reconstructed data were used to assess water resource yields in the R. Eden (north-west England), R. Great Ouse, R. Nene and R. Welland catchments (Wade et al., 2006) using flow data extended back to 1800 (Jones et al.,

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[2] Deployable Output is the output of a source as constrained by yield, licence conditions, pump capacities, raw water losses, works capacity and water quality considerations.

[3] Water Industry Act 1991 Section 37 A to D, as amended by the Water Act 2003.

[4] Water Industry Act 1991 Section 39 B to C, as amended by the Water Act 2003.

[5] These gauges, and periods of records, are: Upton 1939–2013, St. Andrews 1939–2013 and Dodford 1945–2013.

2006b) with the same techniques used previously (Jones et al., 2006a). The flow series generated by these studies have subsequently been used to assess the impact of long and severe 19th century droughts on drought management at two reservoirs: Grafham (Anglian region, Fig. 2) and Wimbleball (south-west England) (Watts et al., 2012; Von Christierson et al., 2009). Indirect methods with tree-ring data have been applied to reconstructing precipitation (e.g. Eastern Turkey, Touchan et al., 2003) and river flow (e.g. Western USA, Meko et al., 2001) but the technique is more useful for summer season estimates rather than for the UK where winter rainfall is more important. However, none of these studies utilised reconstructed data to address the regional impact on water resources or drought management.

1.4. Study justification and objectives

The drought of 2010–2012 focussed attention on the fragility of water resources in parts of central, southern and eastern England (Kendon et al., 2013). Across the Anglian region the dry winter of 2010/2011, followed by a very dry spring, coupled with record high Soil Moisture Deficits from March to June 2011 resulted in river flows approaching recorded minima. Consequently the region-wide total reservoir storage failed to meet target in spring 2011 and progressively declined until November 2011. Furthermore there was concern that below average rainfall during winter 2011/2012 and an unprecedented winter with below average rainfall and river flows in 2012/2013 would place considerable stress on water supply and the environment (Environment Agency, 2012b; Anglian Water, 2014a). This concern over the impact of a long-duration drought, coupled with the earlier studies indicating long, intense 19th century multi-season drought episodes (Jones et al., 2006b; Wade et al., 2006) and the tentative evidence of gradually emerging climate change (Rodda and Marsh, 2011) prompted a region wide study to assess the response of reservoir supply systems in the Anglian region over a longer period than that previously carried out.

The objectives of the study were:

- To produce daily rainfall and potential evapotranspiration for the period 1798–2010.
- To simulate daily river flows for the period 1800–2010.
- To use the 211 year daily river flow series for simulation of reservoir behaviour and yield analysis.
- To compare the severity of droughts in the periods 1920–2010 (the period normally used for water resources planning) and 1800–1919.
- To assess the significance of pre-1920 droughts for Water Resource and Drought Management.
- To assess the potential use of long historic series for improving the resilience of water supply systems to drought under current climate.

The paper is organised as follows. In Section 2, we outline the methodology used to simulate reservoir storage and assess reservoir yield and describe the study area. Section 3 details the production of climatological data. Section 4 describes rainfall-runoff models, the simulation of daily river flows for key catchments, reservoir simulation and yield assessment for 5 reservoirs. Section 5 describes characteristics of the long river flow series and presents the results of reservoir simulation. Section 6 compares the results with previous work, reviews uncertainty, considers the implications for water resources and drought management and outlines the potential for wider application of methods. Conclusions and recommendations close the study.

2. Outline methodology and study area

2.1. Outline methodology

The standard methodology used by Anglian Water for reservoir simulation and yield analysis was employed for the study (see Fig. 1). The main differences from this approach were:

- The period of reservoir yield analysis was extended from 90 to 211 years.
- Rainfall data reconstruction used individual rain gauges coupled with UK Met Office quality controlled 5 km × 5 km gridded data. The process is described more fully in Section 3.1.
- A temperature-based method, using the Central England Temperature series (Met Office, 2011b; Parker et al., 1992) was used to calculate potential evapotranspiration (PET). This is described in Section 3.2.
- Existing rainfall-runoff models were updated and where necessary recalibrated with the new daily rainfall and PET series. This is outlined in Section 4.1.

2.2. Study area

Eastern England is the driest region in the UK, receiving an annual average rainfall for the period 1970–2000 of 606 mm, approximately two-thirds of the average for England and Wales (Met Office, 2013). Combined with an annual average actual evapotranspiration of 450 mm, this gives an annual average effective rainfall of only 156 mm, the lowest in the UK. Against this challenging climatic backdrop Anglian Water supplies 1100 Ml/d of drinking water to 4.2 million customers over an area of 27,500 km^2 (Fig. 2). Approximately 50% of water supplied is abstracted from groundwater, 5% from rivers for direct supply and 45% from reservoirs filled by direct inflow and/or pumping from rivers. The catchments from which water is pumped into reservoirs are predominantly underlain by impermeable shales and clays in the south-west and south-east (dominated by surface runoff – Base Flow Index (BFI) in the range 0.50–0.60) and by the Chalk aquifer in the north (BFI: 0.85–0.90). This paper focuses on the five largest of the eight Anglian Water reservoirs summarised in Table 1, the locations of which are shown in Fig. 2.

The simulated response of Anglian Water's reservoirs to droughts since 1920 is variable, with critical periods (defined as the period during which a reservoir goes from full to minimum storage without spilling in the intervening period (McMahon and Mein, 1986)) ranging from 6 to more than 30 months, depending on the type, capacity and location. For the largest pumped storage reservoirs, Grafham, Rutland and Pitsford, the critical period is around 20 months, lasting through three seasons, i.e. two summers and the intervening winter[6]. Drought duration from analysis of post-1920 data (defined here as the critical period plus the time taken for the reservoir to regain full storage) is also variable, with simulated responses of 44 months at Grafham, 45 months at Rutland and 34 months at Pitsford.

3. Production of rainfall and potential evapotranspiration data

For simulation of daily river flows from 1798–2010 for the 13 catchments across Eastern England that provide water to the 5 reservoirs included in the study, the key requirements are daily rainfall and potential evapotranspiration (PET). These 13 catchments comprise 9 from which water is pumped to reservoirs and 4 that drain directly into reservoirs (see Table 1). The need for daily data

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[6] Summer is defined as April–September and winter as October–March.

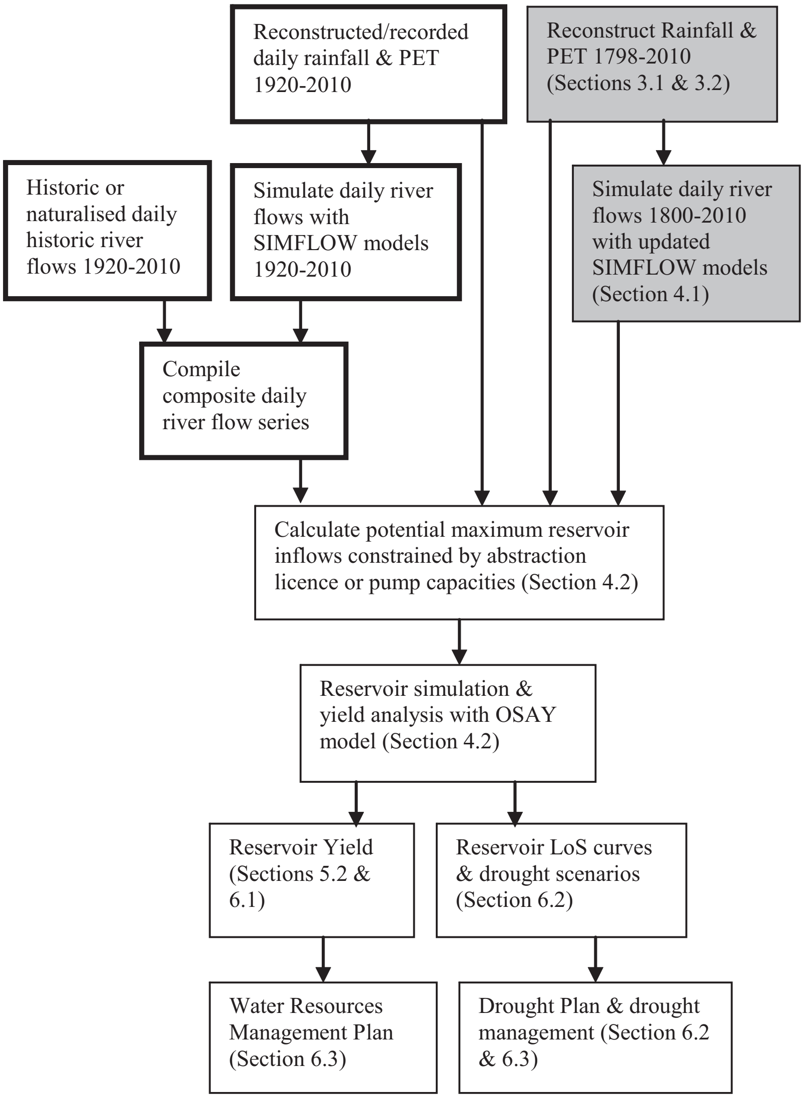


Fig. 1. Outline methodology used in the study. Boxes outlined in bold indicate the method for preparation of rainfall and potential evapotranspiration (PET) and river flow data normally used, and replaced in this study by the different methods in boxes shaded grey.

series arises from (a) the requirement 'to simulate the realistic operation of water resources system in question using a simulation model with a daily or other appropriate timestep' (Environment Agency, 1997) and (b) the need for daily operational decision-making due to constraints imposed by water abstraction licences with daily limits and residual flow requirements, and pump sizing. The continued use of a daily timestep is important for consistency with previous analyses used in WRMPs and DPs and the potential application of results from this study for updating those plans.

3.1. Rainfall

The primary source of rainfall data is the UK Met Office quality controlled 5 km × 5 km gridded data, for which monthly data are available for the period 1910–2010 and daily data from 1958–2010 (Perry and Hollis, 2005). The purpose was therefore to reconstruct a daily gridded dataset for 1798–1957 and then to produce daily catchment series for 1798–2010. The main steps in this process are summarised in Fig. 3.

Of the 36 'composite' rainfall series resulting from **Steps 1–3**, only 3 have recorded data before 1807, Oxford, Kew and Spalding, with the majority (28) starting recordings between 1835 and 1875. The 36 gauges provide better spatial coverage compared with the 22 previously available (Fig. 2). Five of the gauges, those at Kew (London), Oxford, Mansfield, Epping (north-east London) and Shifnal (Shropshire) are outside the Anglian region. The first four are important sources of early data, while Shifnal was included for coverage in the north-west of the region but plays a very minor role in rainfall reconstruction. There are uncertainties in the resulting composite series, such as changes in windiness affecting annual rainfall totals and greater under-catch in winter totals during colder periods such as the early 19th century when a larger proportion of the winter precipitation would probably have fallen as snow. Winters with substantial snowfall would increase the duration that precipitation is stored in the snow pack and increase the time to appearance as runoff. Although there is little that can be done to remove this uncertainty it potentially causes an issue for rainfall-runoff modelling that is discussed later.

In **Step 4** rain gauge infilling was carried out from 1798 to the year before recorded data are available and from the year after data ceases to 2010 (Fig. 4). The assumption that the inter-station relationships from the adopted period, 1880–1920, can be applied to other periods is supported by good correlations between recorded and infilled data. This is demonstrated with the recorded data for

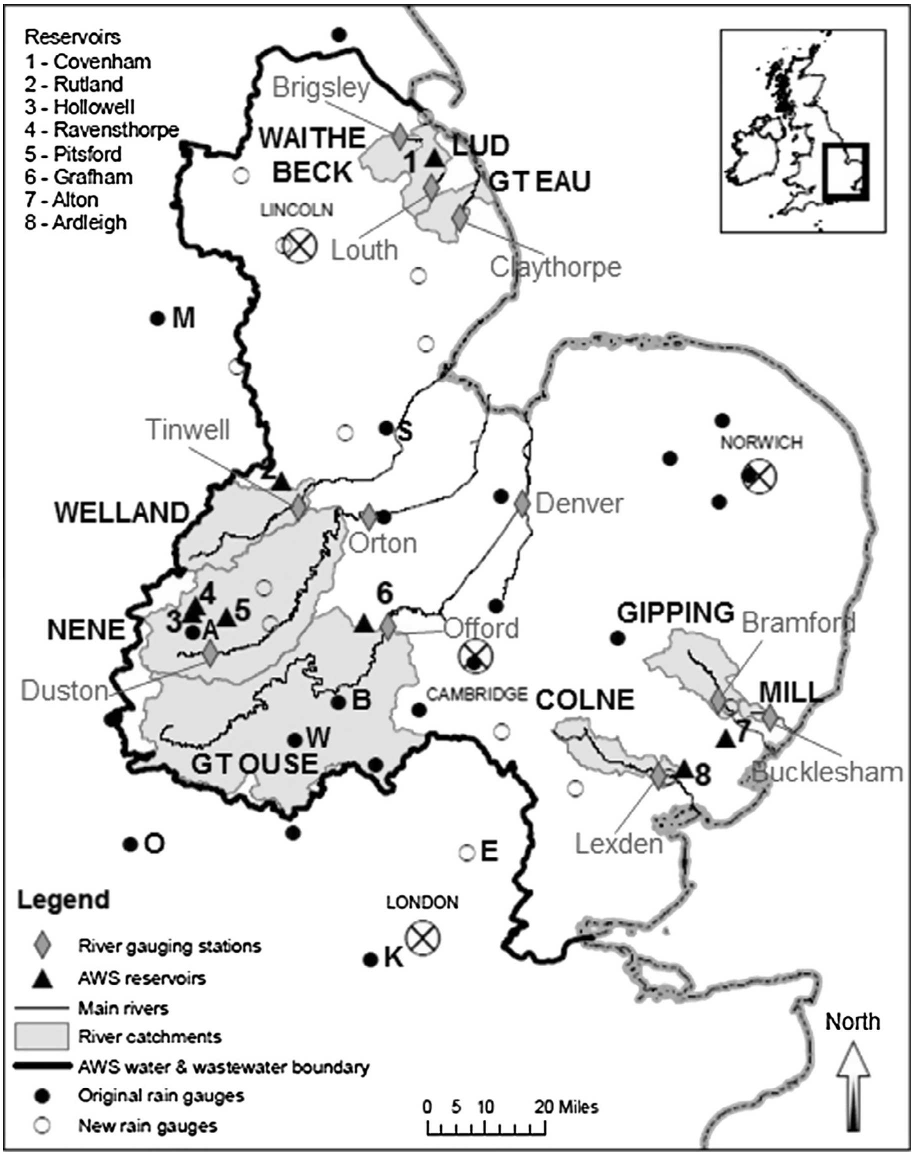


Fig. 2. Location of original and new series rain gauges, reservoirs and catchments from which water is pumped to Anglian Water Services (AWS) reservoirs in the Anglian region (UK). Rain gauges discussed in the text are: K Kew, E Epping, O Oxford, S Spalding, B Bedford, A Althorp, M Mansfield and W Woburn (also a snow measurement site). Note that one rain gauge at Shifnal, located in the north-west Midlands, is not shown. The reservoirs and catchments used in the study are Covenham (R. Great Eau to Claythorpe; Waithe Beck to Brigsley; R. Lud to Louth), Rutland (R. Nene to Orton; R. Welland to Tinwell), Grafham (R. Great Ouse to Offord), Pitsford (R. Nene to Duston) and Alton (R. Gipping to Bramford; R. Mill to Bucklesham).

each gauge and data infilled using Oxford, Spalding and Kew, the only three gauges available for infilling over the period 1798–1806 (Fig. 5). Using only Oxford and Spalding for infilling gives, on average, slightly reduced correlations at most gauges (mean r value for Oxford and Spalding = 0.84 compared to mean r for Oxford, Spalding and Kew = 0.86). An example of infilling is given in Fig. 6, where the Bedford rainfall data are only available from 1846–1980. Infilling was carried out for the period 1798–1845 using data available from the 3 nearest gauges for which data were available. These were at Oxford (data available 1798–1980), Kew (1798–1975), Spalding (1798–1975), Epping (1822–1923) and Althorp (1841–1975). For the period 1798–1821 the 3 nearest gauges for which data were available for infilling were Oxford, Kew and Spalding. The correlation coefficient for the period of overlap between calculated and recorded monthly data, 1880–1920, is $r = 0.91$. The infill process uses nearer gauges as data become available: Oxford, Kew and Epping from 1822–1840 ($r = 0.89$) and Oxford, Epping and Althorp from 1841–1845 ($r = 0.92$). Further evidence of the long-term stability of inter-station relationships is demonstrated by either minimal or non-existent long term trends in annual rainfall. For example, the Bedford infilled annual series indicates no long term trend in average annual rainfall during 1798–1980 (Fig. 6).

As a measure of the gauge-to-grid error in calculation of monthly gridded data (**Step 6**), the standard deviation of the annual ratio between the 36 gauge records and their nearest grid squares for the period 1910–1960 was calculated. This indicated that for 95% of annual totals the gauge-to-grid error for 20 gauges is less than ±10% and for the remaining 16 gauges ±11% to ±16%.

In the derivation of daily catchment series for the period 1798–1957, where gridded data had been derived by pattern scaling (**Step 8**), a different pattern scaling method was used to convert monthly to daily gridded rainfall. This was done because the month/year used to provide the pattern in **Step 7** may have been different for adjacent grid squares and simply deriving a weighted average of the daily grid square series would tend to produce a

Table 1
Anglian Water operational reservoirs. Direct catchment areas exclude the surface areas of reservoirs. Reservoirs used for the study are shown in bold.

Reservoir	Reservoir type	Storage Capacity (Million Cubic Metres)	Surface Area (km^2)	Catchment from which Water Pumped to Reservoir (Flow Gauging Station)	Base Flow Index[a]	Catchment Areas (km^2) (No. of Catchments)	
						Direct	Pumped Sources
Alton	**Pumped storage impounding reservoir**	**9.46**	**1.64**	**R Gipping (Bramford)** **Mill River (Bucklesham)**	**0.50** **0.92**	**17.5 (1)**	**328 (2)**
Ardleigh	Pumped storage impounding reservoir	2.19	0.53	R Colne (Lexden)	0.52	12.4 (1)	256 (1)
Covenham	**Pumped storage reservoir**	**10.67**	**0.89**	**R Lud (Louth)** **Waithe Beck (Brigsley)** **Gt. Eau (Claythorpe)**	**0.90** **0.85** **0.89**	**nil**	**292 (3)**
Grafham	**Pumped storage impounding reservoir**	**53.28**	**6.25**	**R Great Ouse (Offord)**	**0.50**	**9.8 (1)**	**2567 (1)**
Hollowell	Impounding reservoir	1.93	0.5	R Nene	N/A	9.9 (1)	nil
Ravensthorpe	Impounding reservoir	1.63	0.45	R Nene	N/A	11.7 (1)	nil
Pitsford	**Pumped storage impounding reservoir**	**15.35**	**1.99**	**R Nene (Duston)**	**0.60**	**47.4 (1)**	**310 (1)**
Rutland	**Pumped storage impounding reservoir**	**112.0**	**11.46**	**R Nene (Orton)** **R Welland (Tinwell)**	**0.51** 0.51	**63.5 (1)**	**2064 (2)**

N/A = not available.

[a] Marsh and Hannaford (2008).

smoothed series with very few completely dry days and few days with high rainfall. The characteristics of flow simulated from such a rainfall series would be very different from that using recorded daily data from 1958 onwards. To overcome this problem a regional rainfall series, an average of all grid squares, was used. From this series the same month was selected for applying the daily pattern to all grid squares within each catchment. The use of the regional rainfall series was justified because of (a) the current level of integration of the Rutland–Grafham–Pitsford reservoir system and the preference for applying a consistent pattern selection across their aggregated catchments, and (b) possible future integration of the Anglian supply system.

3.2. Potential evapotranspiration

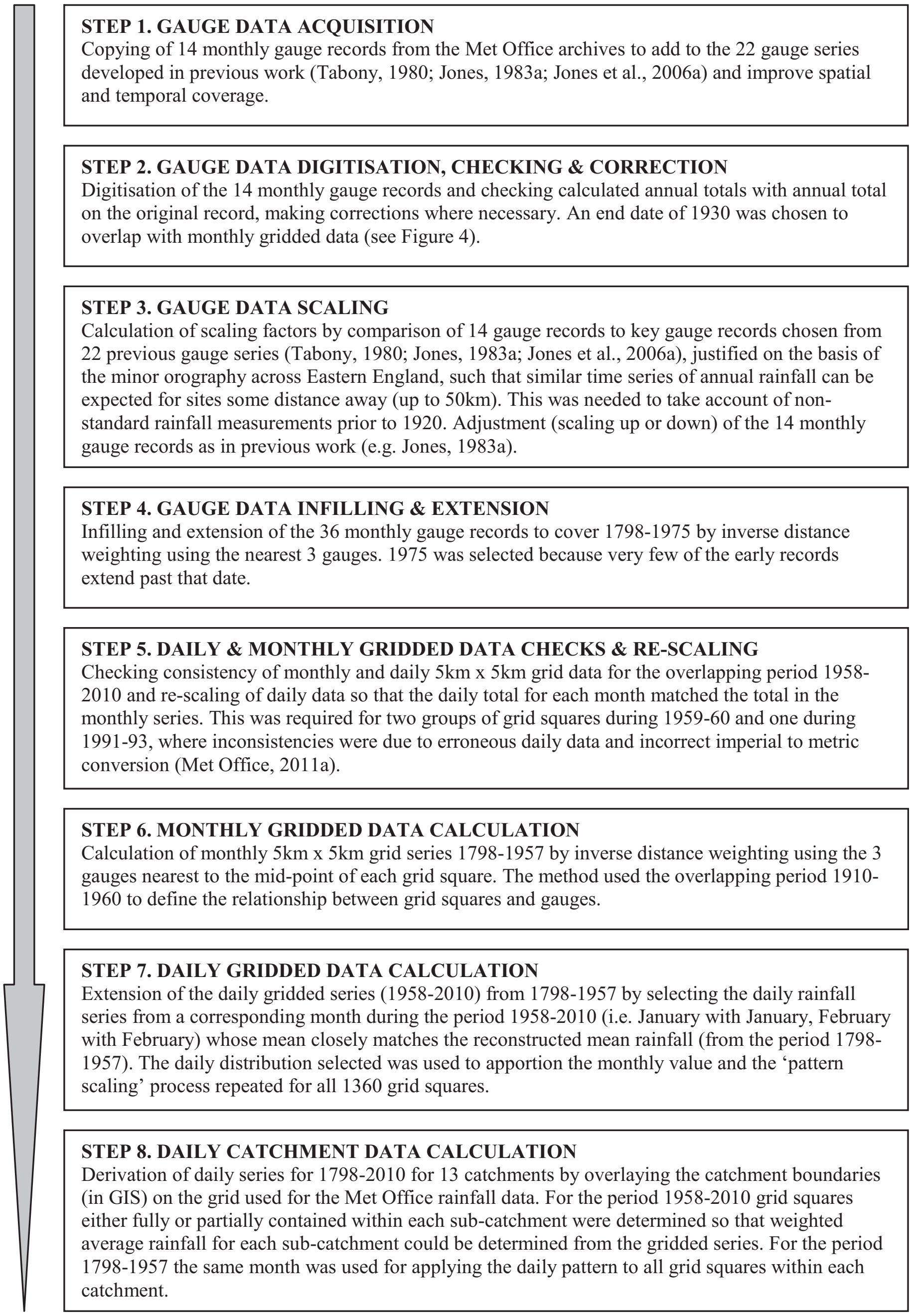
The rainfall-runoff models used in surface water resource assessment require daily potential evapotranspiration (PET) series. In the past PET data for these models was derived from the Meteorological Office Rainfall and Evapotranspiration Calculation System (MORECS) (Hough and Jones, 1997) run by the UK Met Office, based on 40 km × 40 km grid squares covering the Anglian region. Meteorological data input to MORECS are daily rainfall, sunshine hours, mean daily temperature, wind speed and humidity and evaporation is calculated by the Penman–Monteith equation (Monteith, 1973). The MORECS PET data are weekly for the period 1961–2011 and, for the 13 squares relevant to the models were extended back to 1918 in earlier work by estimating PET from climate data (Mott MacDonald, 1997). Adjustments were made to ensure continuity with MORECS data from 1961 onwards. The monthly data for the period 1918–1960 were converted to half-monthly data using the average relationship between each half-monthly mean and the relevant monthly mean derived from the 1961–1996 MORECS data. The daily PET series for rainfall-runoff modelling were then based on constant values for each half month for the period 1918–1960 and constant values for each period of 7 days for the period 1961–2010, derived by equal division of weekly MORECS data.

Because there is very limited data available for the range of climate variables required to calculate PET with a physically based method such as MORECS, a different method was used to reconstruct daily series for the period from 1798 to 1917. The main steps in this process are summarised in Fig. 7, and involve the use of the Central England Temperature (CET) series (Met Office, 2011b; Parker et al., 1992) to extend PET (**Steps 1 and 2**). Comparison of CET and temperature data for individual MORECS squares for the period 1961–2010 shows varying agreement, reflecting the decrease in temperature from south to north, with the best agreement in central East Anglia.

PET from temperature based models may differ from that calculated with physically based models such as MORECS (Sheffield et al., 2012) and contribute to errors in the calculation of drought indices (Dai, 2011). However, it has been shown that for several temperature based models agreement with measured evaporation may be improved by using locally calibrated parameter values, producing similar estimates for different models (Xu and Singh, 2001). One of these, the Thornthwaite method (Thornthwaite, 1948), was used to estimate monthly PET for the period 1798–2010 from temperature data and the average day length for each month (**Step 3**). The resulting Thornthwaite monthly means were found to be lower than MORECS from January to May but higher for the rest of the year. A simpler approach than re-calibrating parameter values was used for correcting the bias in Thornthwaite estimates: calculation of monthly adjustment factors by comparing Thornthwaite PET and MORECS PET and applying these over the period 1798–1917 (**Step 4**). The relationship between MORECS and Thornthwaite is not consistent across the decades 1961–70 to 2001–10. There are some large differences in winter months, but given the low level of PET during these periods the effect in absolute terms would be small. There is relatively little variation in the months with average or above average PET; from April to September the range across the decades is between ±3% and ±7%. Estimation of final PET series for each MORECS square is described in **Steps 5 and 6**.

4. Rainfall-runoff and reservoir modelling

The Anglian Water models used in the study to simulate river flow and reservoir storage have, since 1997, followed the Environment Agency methodology (Environment Agency, 2012a) for producing WRMPs. Similarly, the same models have, since 2000,



STEP 1. GAUGE DATA ACQUISITION
Copying of 14 monthly gauge records from the Met Office archives to add to the 22 gauge series developed in previous work (Tabony, 1980; Jones, 1983a; Jones et al., 2006a) and improve spatial and temporal coverage.

STEP 2. GAUGE DATA DIGITISATION, CHECKING & CORRECTION
Digitisation of the 14 monthly gauge records and checking calculated annual totals with annual total on the original record, making corrections where necessary. An end date of 1930 was chosen to overlap with monthly gridded data (see Figure 4).

STEP 3. GAUGE DATA SCALING
Calculation of scaling factors by comparison of 14 gauge records to key gauge records chosen from 22 previous gauge series (Tabony, 1980; Jones, 1983a; Jones et al., 2006a), justified on the basis of the minor orography across Eastern England, such that similar time series of annual rainfall can be expected for sites some distance away (up to 50km). This was needed to take account of non-standard rainfall measurements prior to 1920. Adjustment (scaling up or down) of the 14 monthly gauge records as in previous work (e.g. Jones, 1983a).

STEP 4. GAUGE DATA INFILLING & EXTENSION
Infilling and extension of the 36 monthly gauge records to cover 1798-1975 by inverse distance weighting using the nearest 3 gauges. 1975 was selected because very few of the early records extend past that date.

STEP 5. DAILY & MONTHLY GRIDDED DATA CHECKS & RE-SCALING
Checking consistency of monthly and daily 5km x 5km grid data for the overlapping period 1958-2010 and re-scaling of daily data so that the daily total for each month matched the total in the monthly series. This was required for two groups of grid squares during 1959-60 and one during 1991-93, where inconsistencies were due to erroneous daily data and incorrect imperial to metric conversion (Met Office, 2011a).

STEP 6. MONTHLY GRIDDED DATA CALCULATION
Calculation of monthly 5km x 5km grid series 1798-1957 by inverse distance weighting using the 3 gauges nearest to the mid-point of each grid square. The method used the overlapping period 1910-1960 to define the relationship between grid squares and gauges.

STEP 7. DAILY GRIDDED DATA CALCULATION
Extension of the daily gridded series (1958-2010) from 1798-1957 by selecting the daily rainfall series from a corresponding month during the period 1958-2010 (i.e. January with January, February with February) whose mean closely matches the reconstructed mean rainfall (from the period 1798-1957). The daily distribution selected was used to apportion the monthly value and the ‘pattern scaling’ process repeated for all 1360 grid squares.

STEP 8. DAILY CATCHMENT DATA CALCULATION
Derivation of daily series for 1798-2010 for 13 catchments by overlaying the catchment boundaries (in GIS) on the grid used for the Met Office rainfall data. For the period 1958-2010 grid squares either fully or partially contained within each sub-catchment were determined so that weighted average rainfall for each sub-catchment could be determined from the gridded series. For the period 1798-1957 the same month was used for applying the daily pattern to all grid squares within each catchment.

Fig. 3. Steps in the derivation of daily rainfall series 1798–2010. See text for further explanation. (See above-mentioned references for further information.)

been used under Environment Agency guidance (Environment Agency, 2011) to produce DPs (see, for example, Anglian Water, 2014a, 2014b). In view of this established ‘track record’ only a brief description of modelling techniques follows.

4.1. Rainfall-runoff modelling

Rainfall-runoff models had been developed for all catchments associated with reservoir operation, both those for abstraction and pumped refill and those draining directly into reservoirs. The models were first developed in 1993 and periodically updated (Mott MacDonald, 1997, 2005). The modelling package, SIMFLOW, based on the Stanford Watershed Model (Crawford and Linsley, 1966) is a lumped parameter model and has been in use and under development for over 40 years. The basic inputs are daily rainfall, PET and parametric descriptions of the physical characteristics of the catchment and the primary output is simulated daily streamflow. Most of the model parameters are derived from observed flow or estimated from mapping, whilst parameters describing soil moisture and infiltration characteristics are found by calibration against an observed flow series for the catchment.

In the present study re-assessment of earlier model calibrations was required because these used catchment series based upon individual rain gauges, which have been replaced by the catchment daily rainfall series derived from gridded data. Although there were no major differences in monthly and annual totals, gridded data have fewer days with zero rainfall and lower daily maxima which may change runoff patterns and affect calibration. Each model was run with the new catchment daily rainfall series and the fit of the model (between simulated flow and either naturalised

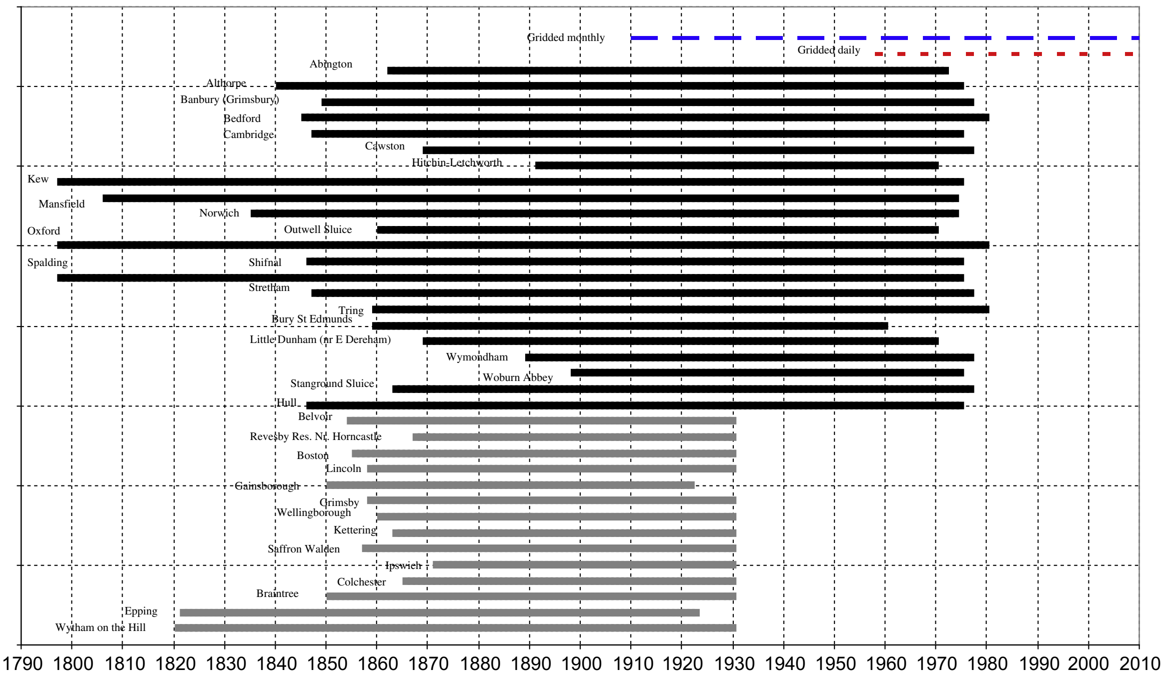


Fig. 4. Details of measured and gridded rainfall data used in the study. Solid black lines are the 22 gauges from earlier work (Tabony, 1980; Jones, 1983a; Jones et al., 2006a; CRU, 2014) and grey lines are the 14 new digitised gauges. Monthly (dashed line) and daily (dotted line) gridded series durations are also shown. Periods from 1798 to the year before measured data are available and from the year after measured data ceases to 2010 were infilled (see text for details).

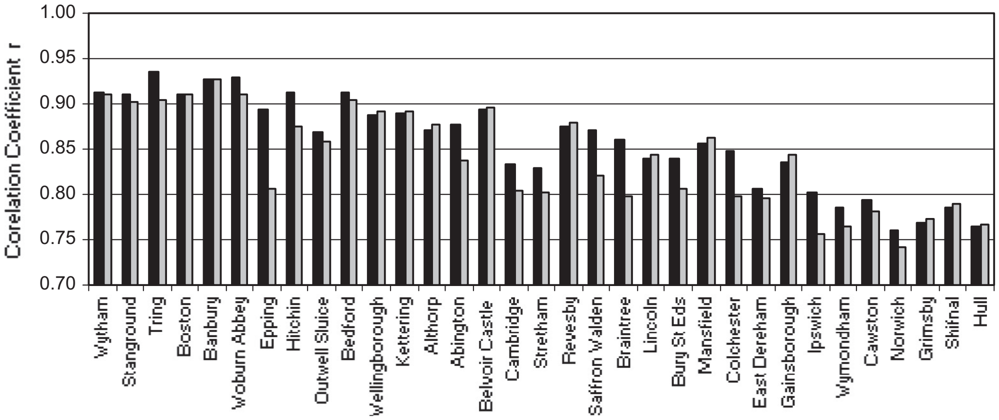


Fig. 5. Coefficients, *r*, for the correlations between recorded and infilled data using Kew, Oxford and Spalding (black) and Oxford and Spalding (grey), ranked by mean distance from Kew, Oxford and Spalding.

or recorded flow) assessed and compared to that in the previous studies (Mott MacDonald, 2005, 2006). This was carried out by visual/statistical comparison of the flow duration curves. The root mean square error (RMSE) of flows in the range between Q50 and Q95 as a percentage of Q50 was the measure used in assessing the performance of simulations. It was found that, using gridded rainfall data, only one catchment, the R Gipping, required re-calibration and for most catchments the agreement between simulated and naturalised or recorded flows over the Q50–Q95 range, mean flows and standard deviations was similar or better than in previous modelling. R Gipping simulated flows were generally over-estimated and this was corrected by reducing the SIMFLOW rainfall adjustment factor by 0.03. This improved the RMSE, although this statistic remained higher than in previous studies.

Rain gauge under-catch due to snowfall is unlikely to have had an effect on model calibration due to the relatively mild winters over the calibration period 1990–2004. To assess the effect of snow, simulated flows were checked at three catchments for which recorded data are available over the very severe 1946/47 and 1962/63 winters: R. Great Eau, R. Great Ouse and R. Colne (Fig. 2). 1962/63 is the 3rd coldest winter in England since 1659 (Met Office, 2014; Parker et al., 1992; Manley, 1974) with snow lying on 69 days at Woburn in the R. Gt. Ouse catchment compared to an average of 11 days (Met Office, 1992). The winter of 1946/47 is the 13th coldest with snow lying at Woburn on 58 days. Recorded flows are higher than simulated during March 1963 in all three catchments due to above average rainfall and milder conditions encouraging snowmelt during that month. Simulated total winter flow volumes are slightly less than recorded. The R. Great Ouse shows a similar response in March 1947, i.e. recorded higher than simulated flows, but total winter flow volumes are similar. In the Tyne, Tees and Eden catchments in northern England, where snowfall is much greater than in the Anglian region, rain gauge under-catch was not found to be of concern when reconstructing flows

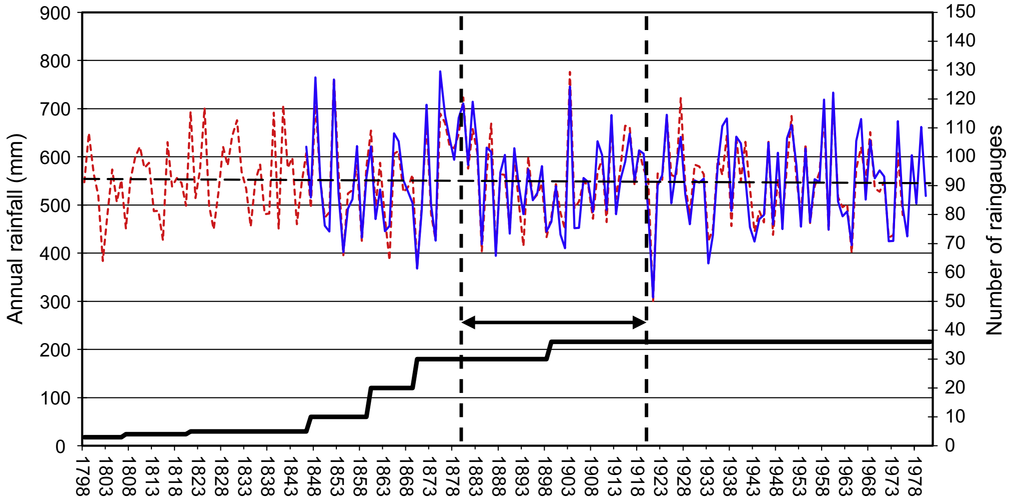
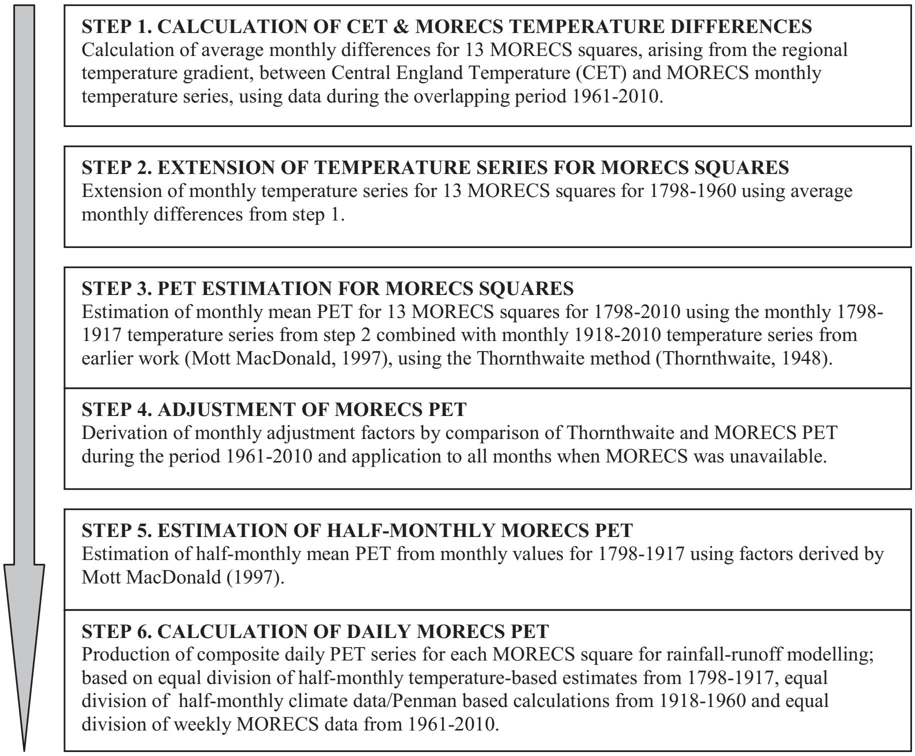


Fig. 6. Comparison of recorded (solid line) and infilled (dotted line) annual rainfall for Bedford. Infilled rainfall is based on the Kew, Oxford and Spalding rain gauges using inter-relationships over the period 1880–1920 (indicated by arrows). The progressive increase in available rain gauges after 1845 is shown by the thick black line. The dashed line shows no long term trend on average annual rainfall between 1798 and 1980.



STEP 1. CALCULATION OF CET & MORECS TEMPERATURE DIFFERENCES
Calculation of average monthly differences for 13 MORECS squares, arising from the regional temperature gradient, between Central England Temperature (CET) and MORECS monthly temperature series, using data during the overlapping period 1961-2010.

STEP 2. EXTENSION OF TEMPERATURE SERIES FOR MORECS SQUARES
Extension of monthly temperature series for 13 MORECS squares for 1798-1960 using average monthly differences from step 1.

STEP 3. PET ESTIMATION FOR MORECS SQUARES
Estimation of monthly mean PET for 13 MORECS squares for 1798-2010 using the monthly 1798-1917 temperature series from step 2 combined with monthly 1918-2010 temperature series from earlier work (Mott MacDonald, 1997), using the Thornthwaite method (Thornthwaite, 1948).

STEP 4. ADJUSTMENT OF MORECS PET
Derivation of monthly adjustment factors by comparison of Thornthwaite and MORECS PET during the period 1961-2010 and application to all months when MORECS was unavailable.

STEP 5. ESTIMATION OF HALF-MONTHLY MORECS PET
Estimation of half-monthly mean PET from monthly values for 1798-1917 using factors derived by Mott MacDonald (1997).

STEP 6. CALCULATION OF DAILY MORECS PET
Production of composite daily PET series for each MORECS square for rainfall-runoff modelling; based on equal division of half-monthly temperature-based estimates from 1798-1917, equal division of half-monthly climate data/Penman based calculations from 1918-1960 and equal division of weekly MORECS data from 1961-2010.

Fig. 7. Steps in the derivation of the daily potential evapotranspiration series 1798–2010. See text for further explanation.

with a monthly time increment, although the focus was on low flows (Jones and Lister, 1998; Jones et al., 2006a). Nevertheless, there remains uncertainty over potential effects of under-catch during the early years of rainfall reconstruction (1813/14, 1829/30, 1878/79 and 1894/95 were notably severe (Met Office, 2014)).

Calibrated models were run with the reconstructed daily rainfall and PET for the period 1798–2010 to produce 211 year flow series (1800–2010) for each catchment. The years 1798 and 1799 were used for model 'warm-up' and were excluded from the final series that formed the basis for reservoir yield assessment and drought analysis.

4.2. Reservoir modelling and yield assessment

The yields of reservoirs have previously been assessed by Anglian Water to support the analysis of the balance of supply and demand for WRMPs (Anglian Water, 2014c). Yield is defined as the maximum average annual demand that could be met by a reservoir, without the storage falling to a pre-determined value, subject to specific constraints such as abstraction licences or pump capacities. The method used was a yield search that provided a demand that could be met in the worst historic drought, the year during which minimum simulated storage occurred. The methodology (summarised in Fig. 1) followed Environment Agency guidelines (Environment Agency, 2012a) for calculating 'Level of Service' (LoS) yield, the yield enhanced by introducing demand restrictions and relaxing licenced abstraction limits during periods of drought and was implemented with the Operating Strategies Assessment of Yield (OSAY) model (Clarke et al., 1980; Anglian Water, 2014b). Firstly, daily potential maximum reservoir inflows are calculated from river flows constrained by abstraction licence or pump capacities. Secondly, OSAY calculates reservoir yield by simulating daily reservoir storage over the full historical period and the method derives storage curves that, when crossed, trigger the introduction of demand restrictions or relaxation of abstraction licence conditions (i.e. augmentation of storage). Typically, there are 3 storage curves, the first triggering the introduction of a hosepipe ban and increased publicity/public awareness, the second restriction of non-essential use and/or relaxation of abstraction licence conditions and the third introduction of rota cuts and standpipes (these are illustrated in Fig. 17a). These measures are each associated with an expected frequency or 'Level of Service', typically 1 in 10, 1 in 40 and 1 in 100 years and are an important feature in DPs. Operating with these storage curves has the effect of increasing reservoir yield, i.e. demand reduction conserves storage and maintains supply at a higher average rate than would have been possible if storage curves had not been employed. OSAY derives the three LoS storage curves as an integral part of the reservoir yield calculation and these are output as three sets of monthly January–December storage values. Each curve defines the storage at which the restriction or augmentation measure starts and ceases to have effect. The model balances the specified LoS criteria, the maximisation of yield and the simulation of storage with a minimum value at or close to 30 days' storage through a process of automatic optimisation and manual sensitivity analysis.

Using the new reconstructed river flow, rainfall and PET data, the OSAY model was run for 2 periods at each of the 5 largest reservoirs, to determine the impact of pre-1920 droughts on reservoir yield:

- 1920–2010, the period normally used for yield assessment.
- 1800–2010, the full period of reconstructed river flows.

5. Results

5.1. Drought characteristics from runoff series

Understanding characteristics of droughts over the 1800–2010 period from the simulated runoff series is a useful pre-cursor to explaining the results from reservoir simulation. There are a range of techniques available for drought characterisation from runoff series (Hisdal et al., 2004; Von Christierson et al., 2009), the most commonly used of which are the *n*-month deficiency method (Cole and Marsh, 2006), the Threshold Level method (Hisdal et al., 2001; Fleig et al., 2006), the Drought Severity Index (Bryant et al., 1994) and the Sequent Peak Algorithm method (Vogel and Stedinger, 1987; Tallaksen et al., 1997).

The *n*-month deficiency approach is the simplest method, involving the accumulation of monthly runoff totals over an *n*-month period (e.g. 12-months, 24-months), expressing these as percentages of the long-term average runoff, and then ranking *n*-month periods that are non-overlapping. It has the advantage that it can be used with a seasonal period, e.g. winter periods that may promote multi-season droughts.

The Threshold Level method employs a threshold flow (e.g. a percentile of the flow duration curve, such as Q70) to define the start and end of each drought period. The flow volumes below the threshold for each period are then calculated and ranked. Different thresholds can be set for each month of the year to avoid a bias towards low flow summer months that would occur when using a single threshold such as Q70 or Q90. The method has the advantage, compared with the *n*-month deficiency method, that discrete drought events are identified by defining the start and end of each period.

The Sequent Peak Algorithm method is similar to the Threshold Level method in that it employs a pre-determined flow threshold to determine the start of a drought. The deficit below the flow threshold is calculated at each time period and accumulated until the deficit is eradicated, usually after the threshold has been exceeded, at which point the drought terminates. Compared with the other three methods the Sequent Peak Algorithm has significant disadvantages, firstly because it tends to identify many very short droughts, and secondly because it fails to identify droughts that occur immediately after major drought events (see Von Christierson et al. (2009), for discussion of these issues).

For the Drought Severity Index method monthly flow anomalies relative to a long-term average flow are calculated and accumulated month by month. A drought begins when accumulated flow anomalies become negative and ends when a pre-defined criterion is achieved (e.g. 3 months of above average flows). The method is sensitive to the termination criterion, which may lead to different interpretations of drought severity and duration. Von Christierson et al. (2009) and Watts et al. (2012) applied these methods to the R. Ely Ouse at Denver Sluice (UK) simulated monthly flow series developed by Jones et al. (2006b) for the period 1800–2002. All four methods identified the same droughts, with minor variations in duration, intensity and ranking due to the arbitrary criteria for setting thresholds, termination criteria or drought periods.

Three catchments from across the Anglian area were used for application of two of the methods reviewed above: the *n*-month deficiency and the Drought Severity Index. For the Drought Severity Index a drought termination period of 3 months was set for consistency with previous studies (Bryant et al., 1994; Mawdsley et al., 1994; Watts et al., 2012). In the context of the similar outcomes identified by Von Christierson et al. (2009) and Watts et al. (2012), these methods were selected because of the relatively simple application compared with the need to set single or multiple flow thresholds (Threshold Level method) and the disadvantages noted for the Sequent Peak Algorithm method. The Drought Severity Index is potentially able to highlight long-duration droughts that could be useful for testing the resilience of water resource systems. Sample catchments were chosen in the north, west and east of the Anglian region:

- The R. Lud at Louth in the north (water pumped to Covenham reservoir).
- The R. Great Ouse at Offord in the west (water pumped to Grafham reservoir).
- The R. Gipping at Bramford in the east (water pumped to Alton reservoir).

For the *n*-month deficiency method 24 and 36 month runoff deficiencies were chosen because they include 2 and 3 winters respectively. The ranked 10 periods of greatest deficiency for these periods are shown in Table 2. For Covenham, 1989–92 is the most severe drought for 24 and 36 month periods, both by considerable margins compared to the second ranked droughts. For Grafham 1857–59 is most severe, followed closely by 1900–03, 1932–34 and 1943–45, although the difference in 24 month runoff deficiency between all four droughts is small. The three most severe 24 and 36 month periods for Alton have similar runoff deficiencies, although 1857–59 and 1932–34 are marginally the most severe.

Winter runoff deficiencies are particularly important in terms of regional water supply. Over winter evaporation losses are modest and during this period most reservoirs are refilled and groundwa-

Table 2
Ranked 24 and 36 month non-overlapping periods of runoff deficiencies (mm) ending on the date given for catchments contributing to Covenham, Grafham and Alton reservoirs. Post-1920 periods are in bold.

Rank	Covenham				Grafham				Alton			
	24 months		36 months		24 months		36 months		24 months		36 months	
	Date	mm	Date	mm	Date	mm	Date	mm	Date	mm	Date	mm
1	**May 1992**	238	**November 1991**	313	October 1859	212	April 1903	281	October 1859	153	**November 1934**	178
2	October 1859	208	**September 1974**	275	April 1903	207	**October 1944**	271	**November 1997**	150	**March 1998**	176
3	**September 1974**	208	**September 1965**	245	**November 1934**	207	October 1859	236	**September 1974**	145	**September 1923**	174
4	**September 1965**	190	November 1864	236	**June 1945**	206	**January 1923**	223	**November 1934**	126	September 1859	162
5	**July 1997**	178	**October 2006**	214	**March 1998**	197	**March 1998**	220	**January 1922**	125	**September 1974**	157
6	**November 2006**	178	**March 1998**	201	**September 2006**	197	**November 1934**	216	**October 2006**	115	May 1903	148
7	September 1835	175	**September 1944**	195	October 1899	193	**August 1974**	213	October 1899	115	December 1864	139
8	September 1899	173	October 1836	177	**January 1922**	181	**July 2006**	204	September 1875	114	**August 1992**	136
9	September 1863	166	October 1859	171	**July 1974**	176	February 1864	198	**March 1992**	109	**July 2006**	119
10	June 1875	161	July 1896	166	September 1906	172	**June 1965**	194	May 1903	107	**August 1950**	104

ter storage is replenished. Major winter deficiencies occur for all three catchments throughout the 1800–2010 period but with more dense clusters in the 1850s, 1860s, 1890s and 1900s, i.e. primarily in the 19th and early 20th centuries (Fig. 8), a feature noted in previous studies (Jones et al., 1997; Marsh et al., 2007; Von Christierson et al., 2009). Consideration of summer runoff deficiency helps to explain the ranking of 24-month and 36-month runoff deficiency and underlines the importance of considering summer and winter conditions when assessing drought severity. For example, at Grafham exceptionally dry winters in the period from November 1857 to October 1859 coupled with moderately dry summers in 1858 and 1859 combine to give the worst 24-month runoff deficiency, ending in October 1859 (Table 2).

The Drought Severity Index identifies the same droughts as the *n*-month method, with sub-regional and reservoir-specific variations in severity and duration due to the influence of the 3 month termination criterion (Fig. 9), a feature noted by Watts et al. (2012). For example, the 1900–03 drought becomes 1897–1903 at Grafham and Covenham, although at Covenham 1900–1903 does not feature in the 10 ranked worst droughts from the *n*-month deficiency method (Table 2). It was found that increasing the termination criterion from 3 to 6 months identified the same droughts but with changes of duration and severity, e.g. the 1853–1857 drought at Grafham became 1853–1860 and ranked worst in the 211 year series. This emphasises the point that the Drought Severity Index is best used for illustrative purposes (Mawdsley et al., 1994). In the 19th century the periods 1853–59 and 1861–66 were extensive droughts across the Anglian region, while 1897–1903 appears extensive mainly in the north and centre. By comparison 20th century droughts are shorter, with 1919–1923 notable in the centre and east and 1988–92 in the north and east.

Most of the droughts identified in this study are consistent with previous work on the R. Ely Ouse to Denver catchment with the exception of droughts during the period 1801–1816, which are ranked as the worst in the 1800–2002 series (Watts et al., 2012; Von Christierson et al., 2009), but do not feature in our *n*-month deficiency analysis, with the 1805–1809 drought ranking only 7th by duration in our Drought Severity Index analysis. Looking further afield there is also consistency with major drought episodes in England and Wales reported by Marsh et al. (2007), notably 1854–1860, 1890–1910, 1921–1922, 1933–34, 1990–1992 and 1995–1997. Sustained drought conditions from 1890–1910 in the English lowlands, described in detail by Marsh et al. (2007), are clearly evident in the Anglian region (Fig. 9) with a succession of very of dry winters in 1889–1891, 1897–1899, 1900–1906 and 1908–1910 (Fig. 8). The extent, severity and impact of the 1890–1910 drought and other major droughts over the period 1800–2002 for the Anglian region and England and Wales are summarised in Cole and Marsh (2006).

5.2. Reservoir simulation and yield assessment

The reservoir yields calculated with the OSAY model, using fully simulated flows and calculated for the two periods 1920–2010 and 1800–2010, are shown in Table 3 and simulated storages for the period 1800–2010 in Fig. 10. As noted earlier the model derives LoS storage curves as an integral part of the reservoir yield calculation so that both may be used to provide the consistency required by the Environment Agency in updating of DPs and WRMPs (Environment Agency, 2012a).

Comparison of the two periods shows that inclusion of pre-1920 droughts does not reduce yields and actually increases yields at five reservoirs, ranging from +1% to +16.6%. The critical droughts for these five reservoirs, indicated by the month of minimum storage, are all post-1920 for both 1920–2010 and 1800–2010 OSAY model simulations. The increases in yield for the long compared with the short period can be explained by the increased number of restriction events allowed over the longer period; the increased restrictions mean that a higher base demand can be supported.

A summary of critical periods and drought durations at the 5 reservoirs for the 10 worst droughts, ranked by lowest storage (drought intensity) is given in Table 4. It is notable that post-1920 droughts define drought intensity in all 5 reservoirs and, with some exceptions, comprise the three worst droughts in the period 1800–2012. The exceptions are Alton Water, where the 1858–1860 drought is ranked 2nd and Covenham, where the 1857–1880 drought is ranked 3rd. The period 1854–1860 emerges as the period of highest ranked drought severity in the period 1800–1920, with lower ranked droughts in that period being dependent on location, for example 1863–1865 at Alton and 1897–1903 at Grafham. Table 4 also highlights the spatial diversity of drought response within the Anglian region. The period 1996–98 is critical at Alton in the east, but ranks between 4th and 8th in the western reservoirs. Conversely, in the west the period 1933–36 is critical for Grafham, Pitsford and Rutland but ranks lower than 10th for Alton. Temporal and spatial drawdown patterns are influenced by geology, topography, abstraction licence conditions, pumping and transmission capacities. For example, Covenham exhibits very long periods of drawdown and recovery due to a combination of groundwater-fed refill, maximisation of yield and imposition of level of service control curves. In contrast, Rutland exhibits frequent short periods of drawdown and recovery influenced by refill from surface water dominated catchments, abstraction licence and pumping constraints.

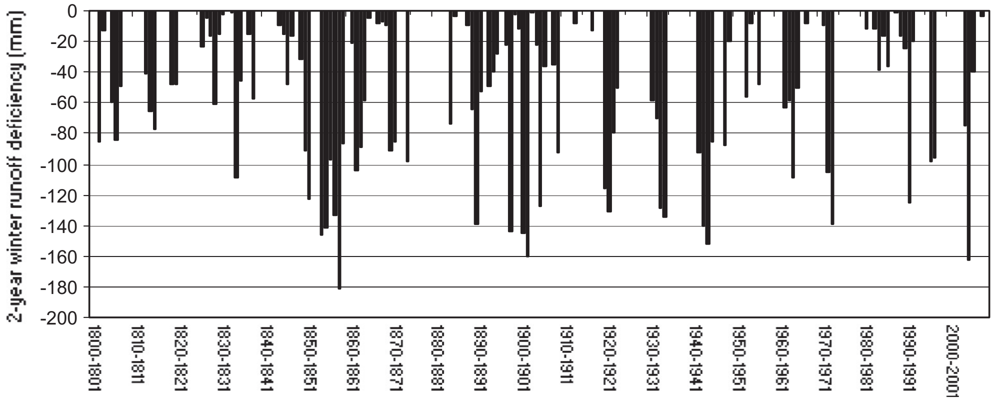


Fig. 8. 2-year winter runoff deficiencies (mm) ending in the period given for Grafham reservoir catchments.

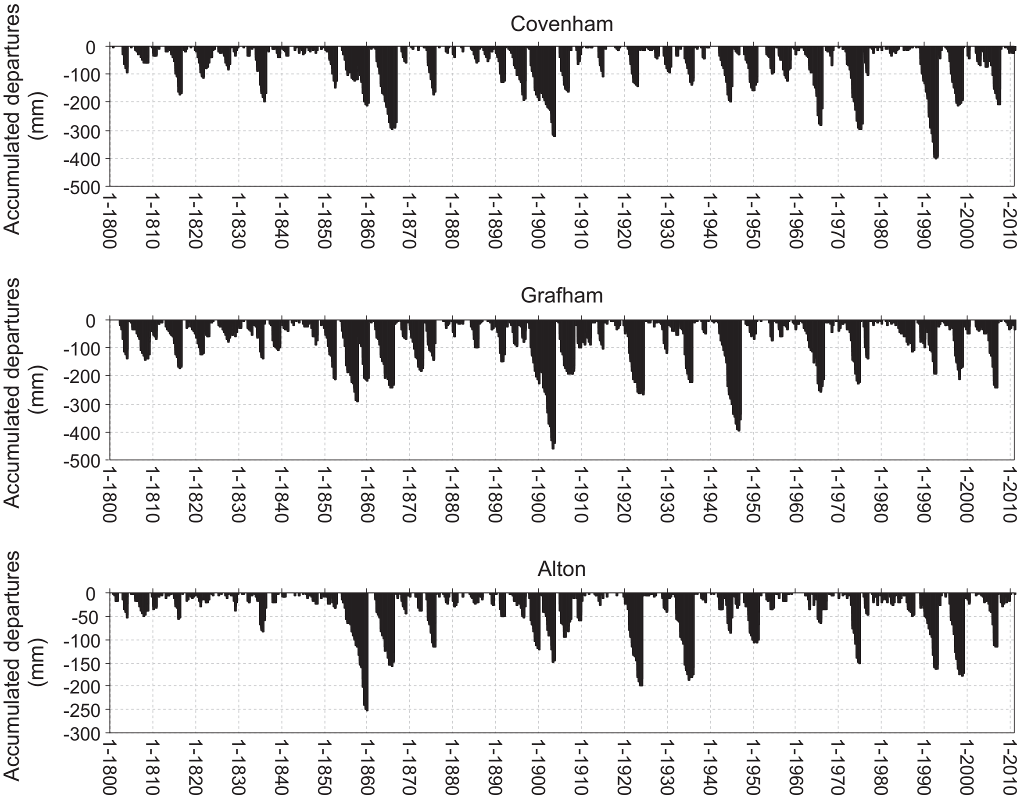


Fig. 9. Drought severity indices for Covenham, Grafham and Alton reservoir catchment flows for the period 1800–2010 using a 3 month termination period.

6. Discussion

6.1. Reservoir yield and uncertainty

A previous study (Wade et al., 2006) used reconstructed rainfall and river flows for the R. Ely Ouse catchment to Denver Sluice from 1800–2002 (Jones et al., 2006b) to assess the yields of Grafham, Rutland and Pitsford reservoirs. Our results are different to those of Wade et al., who showed that for the Nene and Ouse catchments there were droughts in the 19th century that appeared more severe, notably over the period 1802–1807, and produced lower reservoir yields than those post-1920. To allow a direct comparison with the 2006 study the OSAY model was re-run for Grafham, Rutland and Pitsford reservoirs with Wade et al.'s reconstructed river flows (1801–2002). Repeating the model runs was necessary because, firstly, non-LoS yields were assessed in the 2006 work and, secondly, some operational data had changed since 2006, e.g. reservoir refill pump capacity. The results are summarised in Table 3. Using Grafham as an example the key points from these model runs are:

(a) The yield with our 1800–2010 series is lower (288 Ml/d compared to 303 Ml/d) due to the different distribution of flows, as shown by a comparison of flow duration curves

Table 3
Reservoir LoS yields (Ml/d) from OSAY modelling using the periods 1920–2010 and 1800–2010. Results in brackets are re-calculated from previous flow series for 1801–2002 (Wade et al., 2006; Jones et al., 2006b) and are discussed later. Yields for Alton and Covenham were not assessed in the 1801–2002 study.

Period	Yield or critical drought	Alton	Covenham	Grafham	Pitsford	Rutland
1920–2010	Yield	34.5	59.5	247 (314)	40.5 (57.1)	324 (355)
	Critical drought	November 1997	October 1991	November 1934 (January 1922)	November 1934 (November 1934)	November 1934 (December 1934)
1800–2010	Yield	36.5	61.5	288 (303)	43.7 (52.8)	337 (345)
	Critical drought	November 1997	August 1996	November 1934 (November 1803)	November 1934 (December 1803)	November 1934 (November 1803)
% difference in yield between 1920–2010 and 1800–2010		+5.5	+1.0	+16.6 (−3.5)	+7.9 (−7.5)	+13.0 (−2.8)

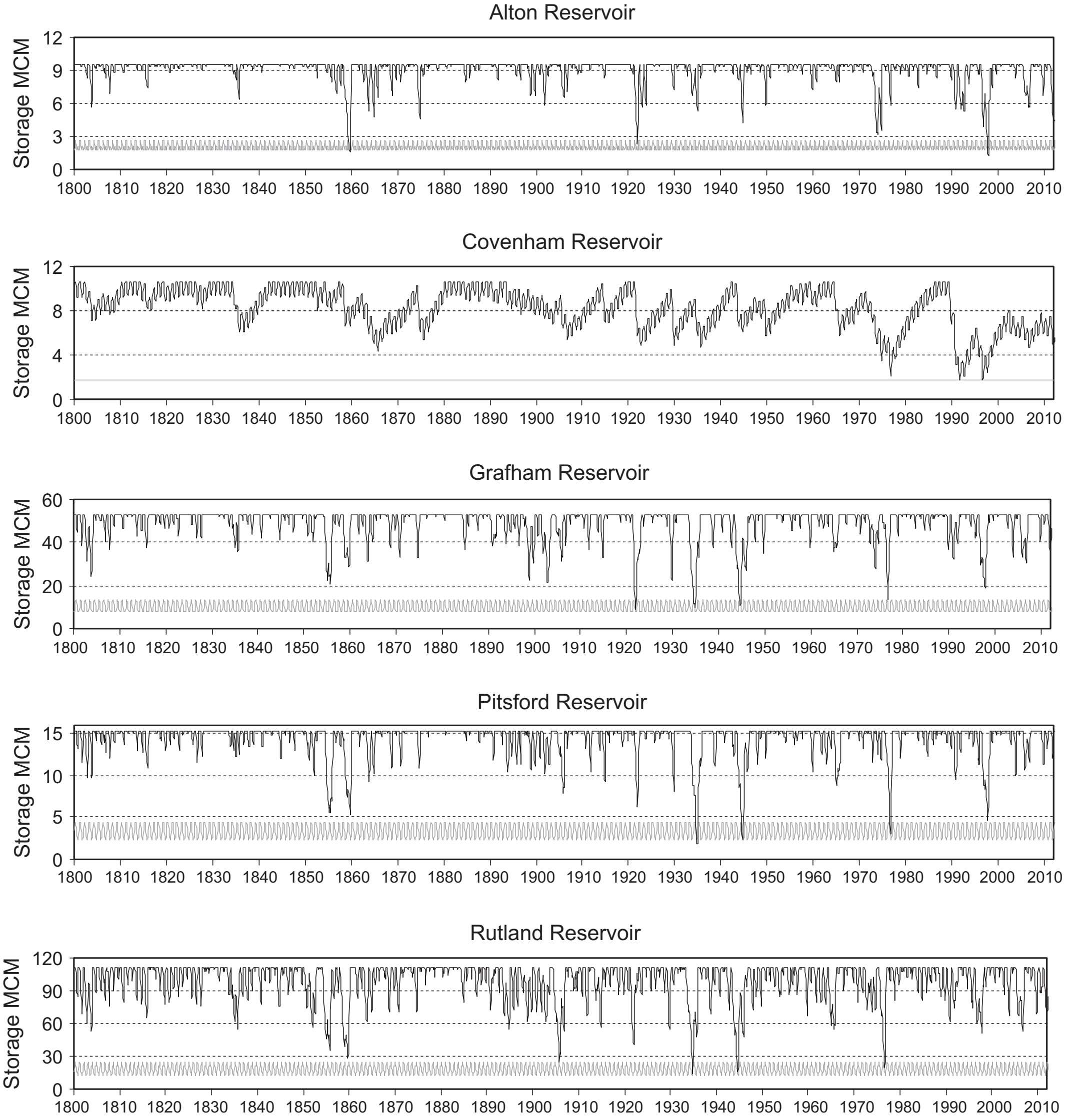


Fig. 10. Simulated storage for 5 reservoirs, 1800–2010. Only the 3rd (lowest) LoS curves (grey lines) are shown for clarity.

(Fig. 11). Our series has lower flows over the bottom half and higher flows towards the top end. For yield assessment it is low flows that are critical, because the constraint imposed by maximum pumping capacity means that increased flows above a certain level, in this case approximately 6 m^3/s, cannot be abstracted.

(b) The critical events are 1933–1934 for our series and 1802–1803 for the 2006 work (Table 3 and Fig. 12). The difference between the two critical periods is supported by drought characterisation from runoff series described earlier, where droughts in the period 1801–1816 are ranked lower for

Table 4
Key drought statistics from OSAY LoS Simulations for 1800–2010, ranked by minimum storage. Drought duration is the period from the start of drawdown to the date when full storage is regained. Post-1920 periods are in bold.

Rank	Alton			Covenham			Grafham		
	Years	Critical period length (months)	Drought duration (months)	Years	Critical period length (months)	Drought duration (months)	Years	Critical period length (months)	Drought duration (months)
1	**1996–98**	20	25	**1989–2010**	40	275	**1933–36**	19	44
2	1858–60	18	22	**1964–87**	149	272	**1921–22**	10	25
3	**1921–22**	11	15	1857–80	101	283	**1943–46**	17	43
4	**1972–74**	19	30	**1921–42**	173	272	**1975–77**	14	22
5	**1944**	8	11	1893–1919	126	275	**1996–98**	17	25
6	1874–75	10	13	**1942–59**	90	201	1854–55	18	25
7	1864–65	8	10				1901–03	18	28
8	1863–64	8	11				**1929–30**	8	14
9	**1991–92**	17	20				1897–1900	16	33
10							1802–04	18	24

Rank	Pitsford			Rutland		
	Years	Critical period length (months)	Drought duration (months)	Years	Critical period length (months)	Drought duration (months)
1	**1933–35**	19	32	**1933–36**	20	34
2	**1943–46**	17	34	**1943–46**	18	45
3	**1975–77**	15	21	**1975–77**	16	22
4	**1996–98**	17	24	1857–60	22	28
5	1857–60	23	28	1904–07	18	37
6	**1921–22**	10	17	1854–56	20	35
7	1854–56	19	21	**1921–22**	11	23
8	1904–06	17	25	**1996–98**	18	25
9	**1929**	8	10	1802–04	20	24
10	**1964–65**	8	20	**2005–07**	19	24

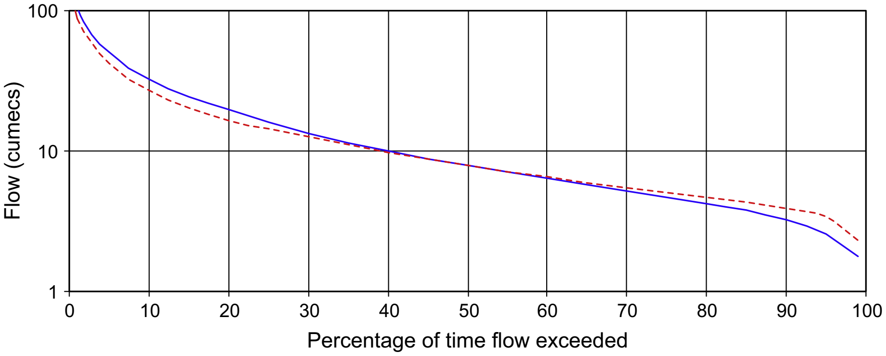


Fig. 11. Flow duration curves for the R. Great Ouse at Offord, 1802–2002, for this study (solid line) and that by Wade et al. (2006) (dotted line). Note that the data are for the period 1802–2002.

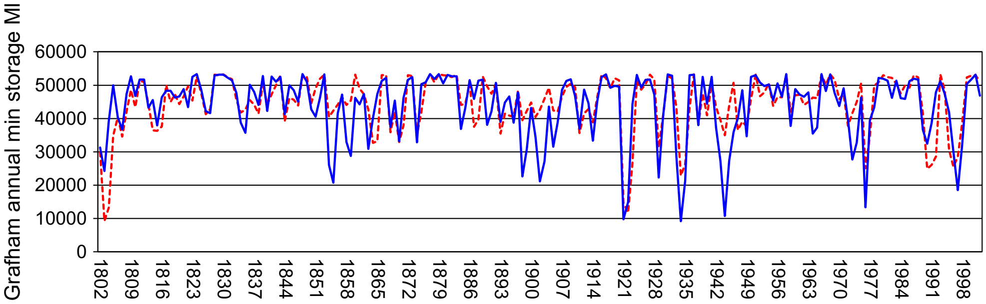


Fig. 12. Comparison of Grafham reservoir annual minimum simulated storage for this study (solid line) and for Wade et al. (2006) (dotted line).

our series (Table 2 and Figs. 8 and 9) than for the 2006 series (Wade et al., 2006; Von Christierson et al 2009; Watts et al., 2012).

Explanation of these points involves consideration of uncertainty in the data sources, principally rainfall, the methods used for deriving gridded and catchment averages and rainfall-runoff modelling. Wade et al. (2006) described this as the ‘cascade of uncertainty’ affecting water resources outcomes and demonstrated that in some cases this uncertainty is greater than future climate change uncertainty.

A comparison of annual rainfall series over the R. Ouse catchment helps to explain the difference in critical drought periods. Although there is generally close agreement over the 1798–2010 period (not shown), there are also some notable differences, particularly from 1800–1817 (Fig. 13). Our series is based on 3 gauges from 1798–1821 (Oxford, Spalding and Kew) whereas the 2006 series used only Spalding and Oxford[7]. Over this period the Kew rainfall was 7.5% higher than Spalding and Oxford rainfall, which although having less influence due to the use of inverse distance weighting, clearly has an impact on rainfall totals. Detailed methods are available for assessing the uncertainty in rainfall series derived from rain gauge networks (e.g. Morrissey et al., 1995; Wood et al., 2000). Here a relatively simple sensitivity approach was used to give a direct comparison of catchment series inclusive and exclusive of the Kew rain gauge. A new R. Great Ouse catchment rainfall series, excluding Kew, was calculated using the infilling, gridded data and pattern scaling procedures described earlier (Fig. 3, steps 4–8). Over the period 1800–1817 the annual totals without Kew were 2.8% lower than those derived with Kew, Spalding and Oxford and 5.1% higher than those for the 2006 series (Fig. 13). The methods used, and catchments covered in calculating areal rainfall may contribute to the 5.1% difference. The 2006 series are for a larger area (R. Ely Ouse to Denver Sluice, 3340 km^2) and calculated using a variant of the Theissen polygon method (Jones et al., 2004), whereas the grid-based series used in this study are for the R. Great Ouse to Offord catchment (2570 km^2). Although uncertainty is likely to be greater in the early years, particularly pre-1820, our series is relatively insensitive to the removal of Kew from the gridded and areal rainfall calculations. Confidence in these years is increased by other published work based solely on the Kew, Oxford and Spalding gauges that considered variations originated only from weather and climate rather than human activity (Todd et al., 2013).

The difference in rainfall totals between the 2006 and our series has an impact on river flows (Fig. 14) and simulated reservoir storage (Fig. 12). There are differences in minimum and maximum annual mean flows, but persistently lower values for the 2006 flow series between 1802 and 1817, giving depressed simulated storage in 1803 (minimum 9.3 Million Cubic Metres (MCM)), with 1802–03 the critical event (Fig. 12). R. Great Ouse flows and simulated reservoir storage were relatively insensitive to the removal of the Kew rain gauge from the rainfall reconstruction. The mean daily flows over 1800–1817 reduced from 13.92 m^3/s with Kew to 13.53 m^3/s excluding Kew. Grafham simulated minimum storage fell, in 1803, from 24.3 MCM to 20.4 MCM, with an identical reservoir yield (288 Ml/d) and critical period (1933–34).

Drought simulation may be influenced by the choice of rainfall-runoff model as well as the reliability of reconstructed rainfall series. 2006 series flows (Jones et al., 2006a, 2006b) were simulated using the monthly statistical model of Wright (1978). The inputs to the model were rainfall and constant values of monthly long-term average actual evapotranspiration, the latter justified on the basis of the achieved modelling accuracy. Possible sources of error in the monthly model are given in Jones et al. (2006a) and dis-

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[7] Although the Kew series was available, it is not reported as having been used in the Wade et al. (2006) study (Jones et al., 2006b), probably because of its distance from the Anglian area.

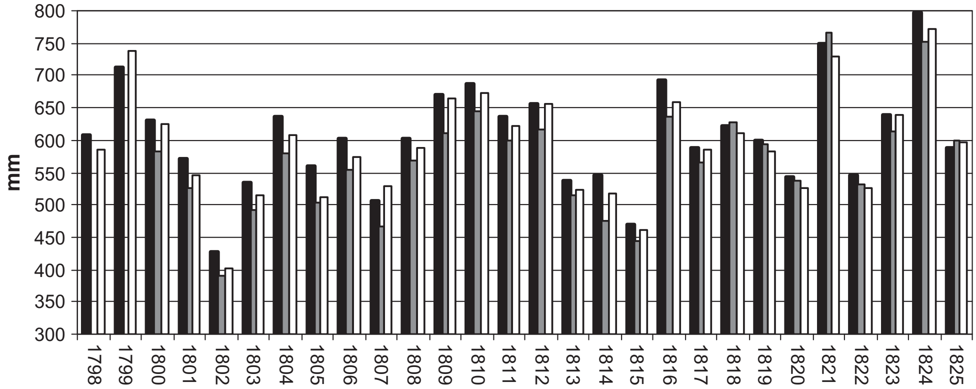

Fig. 13. Comparison of annual rainfall over the period 1798–1825 for the R. Great Ouse catchment to Offord including rain gauges at Oxford, Spalding and Kew (black), only rain gauges at Oxford and Spalding (white) and for the R. Ely Ouse to Denver catchment (grey) (Jones et al., 2006b, Wade et al., 2006).

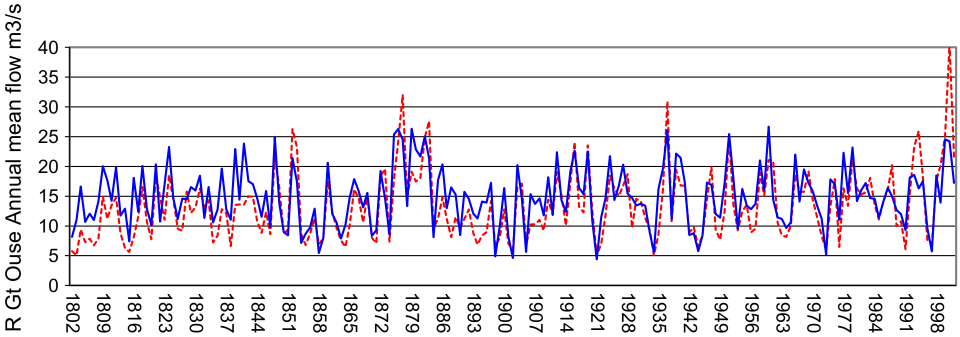

Fig. 14. Comparison of annual mean flows in R. Great Ouse at Offord, 1802–2002, for this study (solid line) and for Jones et al. (2006b) (dotted line).

cussed in Watts et al. (2012). A pattern-scaling method was used to calculate daily *flows* for the R. Ely Ouse to Denver, similar to that used for *rainfall* in this study, and daily flows for the Grafham, Rutland and Pitsford catchments estimated by regression relationships. For the R. Great Ouse to Offord, with a SIMFLOW calibration period of period of 1990–2000, the 2006 series model overestimates naturalised recorded flows over most of the flow duration curve (Fig. 15), whereas our SIMFLOW model shows a closer overall match. The overestimation of flows may be due to a combination of factors: large-scale inhomogeneities in the observed Ely Ouse to Denver series (Jones et al., 2004), the method of *flow* pattern scaling and the use of catchment regressions. This suggests that a more detailed physically-based rainfall-runoff modelling approach such as SIMFLOW is preferable when reconstructing daily flow series (Watts et al., 2012).

Although the pattern scaling techniques used to produce daily rainfall series give unrealistic daily distributions in some months this has not been found to significantly influence the development of past droughts or the calibration of rainfall-runoff models (see Section 4.1). The reasons for this are, firstly, the month to month water balance is maintained because the monthly totals maintain the same structure as the gridded series. Secondly, the pattern scaling of gridded data is based on a regional rainfall series (an average of all grid squares). This means that patterns for individual catchments and adjacent catchments are plausible because they are drawn from recorded patterns for the same period. It should be noted, however, that the daily pattern may affect conditions at the start and end of droughts (i.e. the start of reservoir drawdown and the occurrence of minimum storage). For example, a comparison of flows for the R. Great Ouse in November 1934 shows recovery starting 17 days later in the current compared to previous SIMFLOW model, which lengthens the period the reservoir is drawn down during the final part-month of the drought.

The reliability of the composite daily PET series derived for each MORECS square varies over the period of the series and across the Anglian region due to the calculation and adjustment procedures described in Section 3.2. Our PET series show little variation until 1980, when values increase, consistent with other studies (Burt and Shahgedanova, 1998; Hough et al., 1995). However, Jones et al. (2006a) justified the use of monthly constant values of Actual Evaporation (AE), derived from water balance studies (e.g. Marsh, 2001) on modelling accuracy. They concluded that the use of constant monthly values of AE for simulating monthly river flows was vindicated by modelling accuracy because precipitation was the dominant driver. The implication is that simulated flows are relatively insensitive to evaporation estimates.

6.2. Drought planning and management

The management of water resources and the maintenance of supply during drought in England and Wales are underpinned by DPs drawn up by Water Companies under Environment Agency guidance. DPs include a schedule of measures that would be progressively triggered as conditions moved from ‘normal’, through ‘potential drought’ to ‘drought’, explicit consideration of Drought Orders and Permits, environmental monitoring/mitigation and communications with customers and the Environment Agency. The full list of relevant current legislation is given in the Environment Agency guidelines (Fig. 3 in Environment Agency, 2011). This study provided the opportunity to use a larger sample of droughts over the period 1800–2010 to assess the impact on DPs and to examine the potential benefits for drought management.

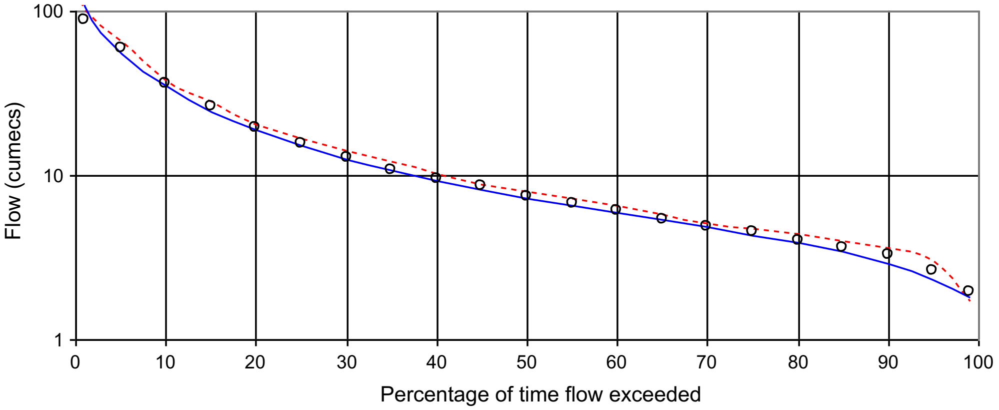

Fig. 15. Comparison of flow duration curves for daily naturalised observed flows for the R. Great Ouse at Offord (circles), the 2006 modelled series (Jones et al., 2006b) (dotted line) and the SIMFLOW series described in this study (solid line). Note that the data are for the SIMFLOW calibration period 1990–2000.

WRMPs and DPs are explicitly linked through the use of the OSAY model, with simulation over the period 1920–2010. In addition to changes in reservoir yield consideration of longer, more intense droughts from the 19th century and early 20th century could lead to modification of LoS storage curves in DPs and the way in which droughts are managed. Evidence from runoff deficiency analysis in the Anglian region and elsewhere in the UK (Von Christierson et al., 2009) suggests that whilst short droughts are evenly distributed across the 19th and 20th centuries, longer droughts were more prevalent in the 19th century (e.g. Grafham catchments, Fig. 16).

From reservoir simulation, however, post-1920 droughts are generally longest, notably those from 1933–36 (Grafham), 1942–46 (Rutland and Pitsford) and 1972–74 (Alton). These periods, together with 1921–22 (Grafham), 1975–76 (Rutland and Pitsford), 1996–98 (Alton) and 1989–2010 (Covenham) also exhibit the greatest reservoir drawdown (Table 4). The 1857–60 and 1890–1910 periods exhibit depressed storage due to a series of exceptionally dry winters but are eclipsed by 1933–36, 1942–46 and 1996–98 with combinations of dry winters and dry summers. Reservoir storage provides a direct measure for assessing the potential impact on the water supply system. In contrast runoff deficiency indices, by using arbitrary termination criteria or durations, are not definitive for drought length or persistence. They do, however, have an important role to play in identification of drought periods for the assessment of drought severity, monitoring and early warning of drought (Von Christierson et al., 2009), particularly for direct supply river intakes, and as such merit further research through application to long series such as those developed in this study.

Drought duration, particularly the potential for a sequence of winters with below average rainfall and river flows, was a concern during the 2010/11 drought, when rainfall in the Anglian region during the 2010/11 and 2011/12 winters was 76% and 64% respectively of the 1971–2000 average (Environment Agency, 2012b). A third successive winter with rainfall and river flows substantially below average would have placed considerable stress on water resources. This scenario, termed ‘the third dry winter’, is characterised by the impact on water resource stocks rather than the statistics of rainfall or river flows. For Rutland, Grafham and Pitsford reservoirs, the key reservoirs of concern in 2011/12, a search of the 211 year series revealed that 1943–46 was the only period with storage below capacity in 3 successive winters. Reservoir storage would have been below capacity for 2 successive winters at Pitsford and below capacity for 3 successive winters at Rutland and Grafham, but only marginally in the third winter, due to above average rainfall and increases in river flows from early 1946 onwards. This emphasises the point that long droughts emerging from runoff deficiency analysis are not necessarily translated to depressed reservoir storage and indicates resilience in the water resources system.

Some parts of the Anglian water resource system are integrated and are able to share resources during periods of moderate drought e.g. the Rutland, Pitsford and Grafham reservoirs. Severe drought episodes are likely to be widespread in the Anglian region, e.g. 1933–36 and 1943–46, and it is uncertain whether surplus resources would be available for transferring to areas of deficit (Von Christierson et al., 2009). Moreover, by the end of the century droughts may be more spatially coherent (Rahiz and New, 2013)

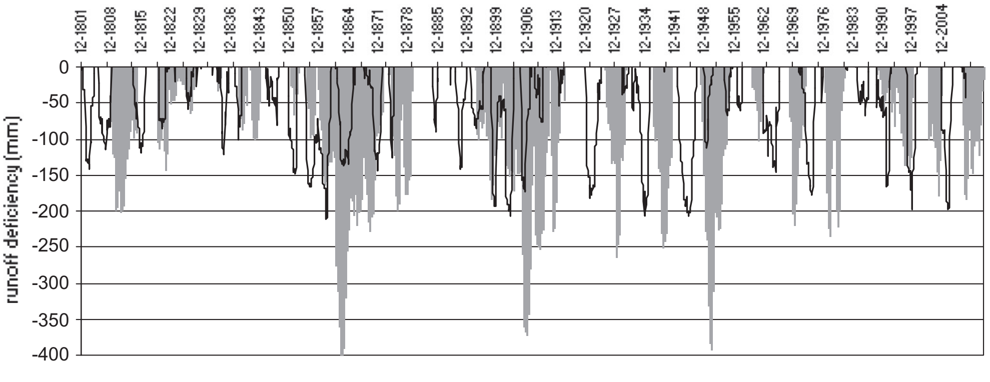

Fig. 16. Runoff deficiency in the Grafham catchments for periods of 24 (black line) and 60 months (grey line).

with an increased likelihood of droughts occurring simultaneously in different parts of the region. Integrated system modelling of the Anglian region is already carried out to assess resilience (Henriques and Fowler, 2009; Henriques and Spraggs, 2011) but could be usefully expanded to include droughts from the 19th century e.g. 1855–1860 and the long drought from 1890 to 1910. This would underpin further integration of the supply system and might include assessment of river and groundwater resources and transfer from catchments outside the Anglian region through further drought reconstruction.

Long runoff series such as those developed in this study could be utilised for projecting reservoir storage scenarios to aid management of water resources during drought (e.g. Hamlin and Wright, 1978) or for testing the resilience of DPs to a range of historic droughts that are outside recent hydrological experience (e.g. Watts et al., 2012). For the 2010–2012 drought reservoir storage projections for Grafham reservoir from October 2011 to September 2012 indicate that demand restrictions would not be introduced even if the most severe inflows (1933/34 and 1943/44) were to re-occur (Fig. 17(a)). A significant factor was the maintenance of storage close to target during 2010 and 2011, during which time 2010/11 inflows ranked only 54th in the 212 year series from 1800 to 2011.

By way of contrast, projections carried out for the 1996/97 drought, starting in October 1997, indicate that there was a potentially high risk of introducing supply restrictions (Fig. 17(b)). The 1996/97 inflows rank 4th in the 211 year series from 1800–2010, only surpassed in severity by 1933/34, 1943/44 and 1975/76. Planning to manage water resources over the 12 months from October 1997 with projections based on any of these four inflow series would have been particularly severe, with return periods greater than 1:1000 years over the 24 month period from October 1996 to September 1998. Nevertheless, the use of specific inflow series of known severity enables the testing of drought management strategy. For example, under the 1996/97 inflow scenario a reduction in reservoir abstraction by 10% from October 1997 to March 1998 and substitution of supply from alternative sources would result in storage being maintained above the LoS Curve 1 without the requirement for demand restrictions. The approach enables the position to be regularly updated so that the consequences of changes in river flow or demand can be monitored and the projections re-modelled (Hamlin and Wright, 1978).

6.3. Implications for water resource management plans and drought plans

Uncertainty in WRMPs is buffered by calculation of a headroom allowance in the balance of supply and demand. Sophisticated probabilistic methods are used to convert uncertainty into headroom. The approach is particularly justified where significant

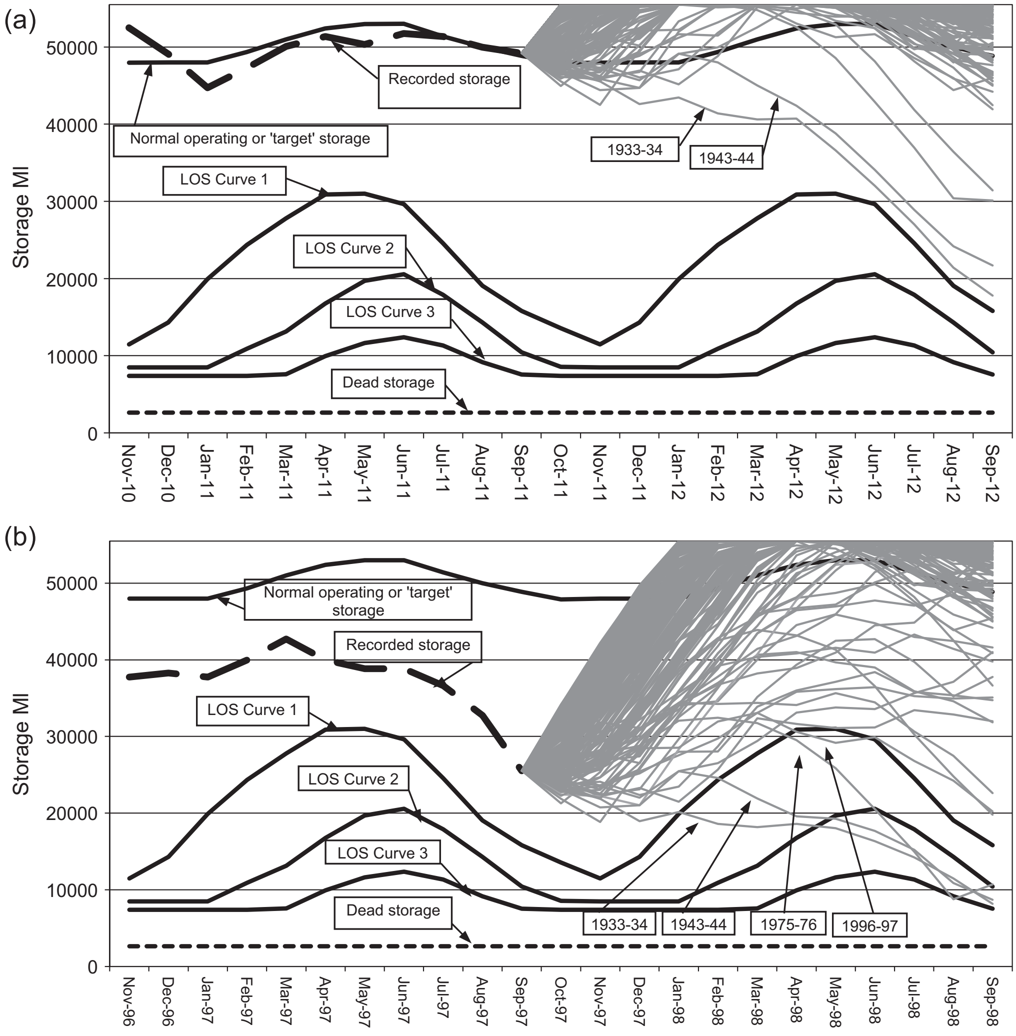

Fig. 17. Grafham reservoir storage projections (grey lines) for (a) the period 2010–2012 and (b) 1996–1998, using all inflow series from the period 1800–2010. Average demand is 220 Ml/d and reservoir compensation release 5.5 Ml/d.

investment may be required (Environment Agency, 2012a). Examples of major sources of uncertainty are the impact of future climate change, short-term unplanned asset failure and changes in projected population growth and per capita consumption. By comparison, confidence is relatively high in hydrological and water resource modelling that forms a basis for deriving reservoir yield and deployable output due to ongoing model development and improvement. The period of model simulation normally used for WRMPs, 1920–2010, continues to define critical droughts and reservoir yields. Simulations extended to 1800 will require more sensitivity analysis before they can be reliably used in WRMPs without increasing uncertainty and potentially affecting headroom. Analysis could usefully include *inter alia* the impact on drought criticality and yield of: varying rain gauge numbers and distribution; different methods of rainfall pattern-scaling; alternative methods of deriving PET; variation of hydrological model parameter values and initial conditions; comparison of alternative hydrological models for sample catchments (e.g. Beven, 2012).

An example of how different hydrological modelling approaches create uncertainty over the response to drought is given by Grafham reservoir during the 1802–1806 period with R. Great Ouse flows simulated for the 2006 study (Jones et al., 2006b) and by SIMFLOW (Fig. 18). For this drought, the worst in the 2006 study, the longer period of depressed storage with the 2006 flow series would instigate extensive supply restrictions under the current drought plan: a 6 months hosepipe ban (LoS 1) and a minimum 1 month non-essential use ban (LoS 2). There would not be any restrictions for this period using the SIMFLOW river flows. Conversely, the worst drought for Grafham in this study, 1933–34, is more extensive than 1802–06, although not as severe. The choice of flow series would have an effect on the LoS curves because, as noted earlier, these are an integral part of the OSAY simulation, i.e. for fixed LoS criteria variation in flow series influences the setting of curves.

Modification of the Level of Service to customers may have a role to play in drought planning. Sensitivity analysis with the OSAY model shows that reducing the Level of Service to customers, i.e. increasing the frequency of supply restrictions, would increase system yield, or alternatively, if yield were not increased, would reduce the risk of supply failure (Anglian Water, 2014c) although the sensitivity to Level of Service varies between reservoirs. Increasing the frequency of supply restrictions is one way of providing additional resilience against more severe droughts and hydrological and modelling uncertainty, but it involves a ‘trade-off’ between WRMPs and DPs and is unlikely to be a popular solution with suppliers or consumers. Other approaches to increasing drought resilience that has been tested, and in some cases implemented involves more flexible abstraction licencing, e.g. allowing higher winter pumping for reservoir refill with compensatory lower summer take, and increasing abstraction pump capacity and flexibility over the expected range of flows.

Droughts differ in terms of onset, duration, intensity, spatial extent and thus impact. To meet this variable characterisation, DPs need to remain flexible to be effective whilst aiming for consistency with WRMPs (Anglian Water, 2014a). Long series of flows that include a spectrum of drought conditions, coupled with sensitivity analysis, have a role to play in testing the robustness of the drought management and water resource planning process.

6.4. Wider application of the methods

The results of this study may not be directly applicable elsewhere due to the unique climate, geology, and hydrology of Eastern England but the methods used could be applied more widely. It was noted earlier that long homogenised rainfall series are available for 15 European countries including the UK and Ireland (CRU, 2014; Tabony, 1980). These data comprise more than 150 European stations, the majority of which started between 1845 and 1870 with a few in the 18th century e.g. Padova, Italy (1725); Hoofddorp, Netherlands (1735); Uppsala, Sweden (1739); Marseilles, France (1748). The UK stations number more than 70, the majority of which started around 1850 but several much earlier e.g. Edinburgh (1785) and Kew used in this study (1697). There are also global and continental climate datasets. The Global Historical Climatology Network (GHCN, 2012; Vose et al., 1992) contains more than 5700 precipitation and more than 6000 temperature stations, with around 10%, concentrated mainly in North America, Central Europe and Eastern Australia, having more than 100 years of data. The United States Historical Climatology Network (USHCN, 2014) includes more than 1200 stations, notably concentrated in the eastern states and extending back to the 1890s. Nicholson et al. (2012) describes rain gauge data availability in Africa, with around 270 gauges in the 1890s, primarily in South Africa and Algeria, some with records starting much earlier e.g. Cape Town and Algiers – 1838. The river gauging network in Europe is extensive and notably dense in the west, including the UK (Hannah et al., 2011) with a 90th percentile record length of 69 years for rivers with greater than 25 years record (McMahon et al., 2007a). In North America (195 gauges), South Africa (48 gauges) and North Africa (40 gauges) the equivalent 90th percentile record lengths are 67, 66 and 51 years respectively (McMahon et al., 2007a). Joint consideration of rainfall and runoff records points to the potential for undertaking climate and hydrological reconstruction across the UK, Europe and other parts of the world to support water resource and drought planning.

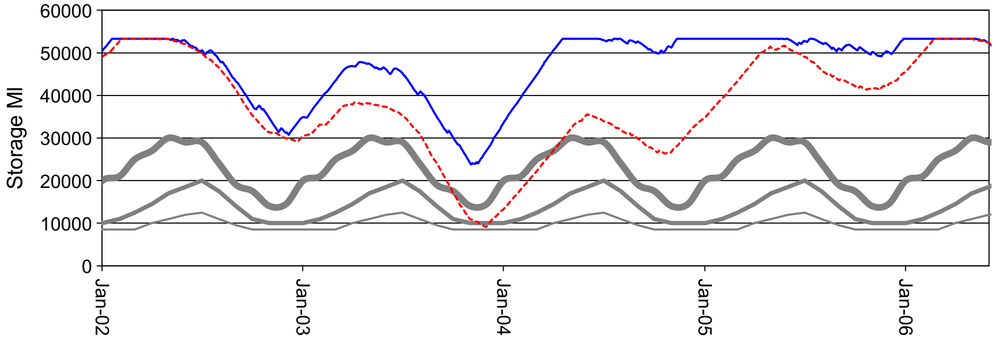

Fig. 18. Grafham reservoir storage simulated with OSAY for the 1802–1806 period using R. Great Ouse flows simulated by the 2006 study (Jones et al., 2006b) (dotted line) and SIMFLOW by this study (solid line). The LoS storage curves (grey lines) are from the current DP (Anglian Water, 2014b): LoS 1 (top), LoS 2 (middle), LoS 3 (bottom).

7. Conclusions and recommendations

A number of conclusions and recommendations follow from this reconstruction of rainfall, PET, runoff and reservoir storage during the period 1798–2010 and assessment of the implications for water resources and drought management.

1. Water resource assessment is frequently practised with data from recent decades but attempts to reconstruct long regional rainfall and river flow series that capture a wide range of historic droughts are rare. Even less common is the application of such long series to assess reservoir resources and drought characteristics across a whole region.
2. Runoff deficiency and drought severity indices indicate that drought episodes in the Anglian region are consistent with those in England and Wales reported elsewhere (Marsh et al., 2007). There is a tendency for greater clustering of dry winters in the 19th and early 20th centuries, which when coupled with dry summers give rise to sustained periods of drought e.g. 1854–60. The severity of specific droughts varies across the region, although the differences in runoff deficiencies may be small and influenced by length of period, e.g. at Grafham the 24 month runoff deficiencies ending in 1859 and 1903 are more severe than 1934 by 5 mm, whereas the 20 month analysis shows 1934 to be the most severe, with 1859 ranked 5th. Despite displaying sensitivity to period length or termination criteria, drought indices have an important role to play in identification of droughts for the assessment of severity, monitoring and early warning (Von Christierson et al., 2009), particularly for direct supply river intakes, and as such merit further research by application to long series as developed in this study.
3. From reservoir simulation pre-1920 droughts were no more severe and reservoir yields not reduced compared with those in the post-1920 period, the period normally used in yield analysis. The droughts of 1933–36 and 1943–46 in the west, 1989–92 in the north and 1996–98 in the east of the Anglian region remain the most severe over the 211 year period of simulated storage in terms of the drawdown of reservoir storage and duration below capacity. The exception is in the east of the region, where at Alton 1972–74 was a longer duration drought. Pre-1920 droughts were similar but of a slightly lower severity than those post-1920. The period 1854–60 is notable in all reservoirs, particularly so at Alton where it ranks the second most severe, and 1893–1907 features widely in the west of the region. Thus, although coherent regional patterns exist, these are tempered by sub-regional variations in drought severity, influenced by rainfall, geology, hydrological response, abstraction licence conditions and refill infrastructure. The continued focus on post-1920 droughts means that neither Deployable Outputs used in current WRMPs nor detailed aspects of current DPs (e.g. reservoir Levels of Service curves) are affected.
4. The extended runoff series is potentially useful during normal and drought conditions for projecting a range of reservoir storage outcomes and quantifying the risk of supply restrictions or interruptions. Such an approach enables the testing of drought management strategy, re-modelling of the projections in response to changes in river flow or demand and regular updating of the water resources position. A selection of historic droughts may also be used to assess system resilience and the robustness of Drought Plans (e.g. Watts et al., 2012).
5. Before implementation of the findings of this study in WRMPs and DPs, the areas of uncertainty emerging from comparison of the study results with published material, data sources, data processing and hydrological modelling, coupled with sensitivity analysis, should be carefully considered. The key points are:
   - The number of rain gauges used (36 compared with 22 by Jones et al., 2006b) and their distribution and conversion to catchment averages may influence the prominence of drought, especially in the first 20 years of the 19th century when only 4 gauges are available (3 in the Jones et al., 2006b, study). Maximisation of the number of gauges and checks for homogeneity improve confidence in results, especially during early periods when data are sparse.
   - However, sensitivity analysis showed that when there are a limited number of gauges removal of one gauge had a minimal impact on areal rainfall, simulated runoff and storage. This, coupled with other published work (Todd et al., 2013) improves confidence in results prior to expansion of rain gauge coverage after 1850.
   - Confidence in reconstructed rainfall series is also improved by use of the quality controlled Met Office monthly gridded series.
   - The pattern scaling technique used to produce daily series where only monthly are available (i.e. from 1798 to 1957) had only a minimal effect on simulated runoff but may influence the timing of drought termination. Further investigation of pattern scaling techniques is recommended.
   - There is uncertainty over the effects of possible rain gauge under-catch during snowy winters in the early years of the 19th century. Although the effects are thought to be small, hydrological model performance could be improved over very cold winters (e.g. 1947 and 1963) in catchments with recorded flows.
   - Sensitivity of results to the methods used for deriving daily PET (principally temperature (Thornthwaite, 1948) and scaling to MORECS PET) was not carried out in this study due to the reported dominance of precipitation in rainfall-runoff modelling (Jones et al., 2006a). However, it would be useful to assess the effect of variation in PET, and of using simpler alternative approaches e.g. constant monthly actual evaporation (Jones et al., 2006a; Wright, 1978) on runoff and reservoir simulation.
   - In comparing statistical and physically-based models the physically-based model used in this study better represented the range of flows important for reservoir refill. This had significant implications for the timing and severity of drought episodes and reservoir yields and underlines the need for careful choice of model and assessment of uncertainty. Ideally, the impact of uncertainty should be assessed over the full suite of data reconstruction, hydrological and water resource models.
6. Some of the most severe droughts identified from runoff deficiency analysis (e.g. 1855–60) do not necessarily emerge as critical from reservoir simulation. This suggests that, although the choice of runoff period may be a factor, there is resilience in the water resources system, albeit that simulation is for single, unconnected reservoirs. Resilience of the current regional water supply network to severe droughts over 1800–2010 could be investigated by integrated water resources modelling. Assessment of resilience would be reinforced by including the impact of future climate change over the full 211 years with an ensemble of climate change scenarios using change factor methods prescribed for UK WRMPs (Environment Agency, 2012a; Von Christierson et al., 2011, 2012). However, due to the fixed structure of historic droughts inherited from long runoff series combined with the change factor approach any increases in drought frequency, severity and duration that might occur due to climate change would not be included because climate models cannot accurately characterise drought structure (Watts and Anderson, 2013).

7. The monthly gridded rainfall series developed in this study could be applied to a much larger range of catchments in the Anglian region, for both hydrological and groundwater modelling. Furthermore, long rainfall and temperature series are available globally, particularly in the UK, Europe and North America, to reconstruct flows using similar methods and assist with water resources planning.

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