Environment
Agency

Impact of long droughts on water resources

Report: SC070079/R5

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Miranda Kavanagh

Director of Evidence

Executive summary

The water resources and drought management plans for England and Wales provide a comprehensive framework for planning future water supplies that addresses economic, social and environmental issues. However, the recent multi-season drought in the south-east of England from 2003–2004 to 2006 and the prospects of a third dry winter in 2006–2007 raised the question of how the current drought management framework would cope with severe long droughts resulting from successive dry winters such as 1854–1860 and 1890–1909. Furthermore climate change is expected to alter drought frequency and duration.

The purpose of this project was to help the Environment Agency test the current drought management framework against severe long droughts. Two different types of system were considered:

- Wimbleball in the River Exe catchment in south-west England;
- Grafham in the Ouse catchment in East Anglia.

The system was tested through two interactive workshops with participation from the Environment Agency, the water companies and Defra using water resources models to ‘role play’ the management of droughts that occurred in 1868–1871, 1886–1888 and 1895–1896 (Wimbleball) and 1801–1804, 1807–1808 and 1815–1817 (Grafham). Participants responded to hydrological situation reports, reservoir levels and actions of other stakeholders to prompt implementation of drought management measures.

In general, the workshops indicated that the drought management framework in England and Wales appears to work well with clear roles and responsibilities for Government, water companies, the Environment Agency and water customers during periods of drought. In the workshops, water supplies were maintained with significant demand restrictions and supply-side measures throughout several years of major droughts. Nevertheless, some of the drought events considered were outside the range of water company experience and presented difficult operational decisions related to water supply, meeting customer expectations and the environment.

The workshop findings indicated the need for further drought planning guidance in the following areas:

- Drought planning guidance should emphasise the importance of adhering to drought plans, including the introduction of demand restrictions during the early stages of a drought. The workshops indicated some reluctance by the water companies to introduce early demand restrictions (including enhanced communication, hosepipe bans and non-essential use bans) at various stages of drought even when different triggers were hit and although such measures were included in their drought plans.
- Drought planning guidance should stress the importance of including all possible drought measures in water company drought plans. Drought plans should be viewed as flexible and practical documents which reflect the full range of measures and actions that may need to be taken by the water companies during different stages of a drought. The workshops indicated that a number of measures used in extreme events were not included in the drought plans, although some were well-established practice.
- Drought planning guidance could encourage water companies more strongly to prepare for drought permits and drought orders well in advance of drought periods. It is recommended that water companies are reminded that the investigations required for drought permits and drought orders

including environmental impact assessments and monitoring plans can be undertaken prior to droughts to speed up the application process (up to 2–4 weeks). Further joint Environment Agency/Defra guidance is needed to clarify the difference between drought permits and drought orders.

- More guidance is needed on how to test the sensitivity of water company drought plans to different kinds of drought including more extreme events not currently considered in the plans. A range of different approaches could be considered from simple sensitivity testing to detailed modelling studies and workshop exercises. Any future guidance should be flexible, allowing for the use of different methods and should consider droughts of different severity, lengths and spatial extent.

- Further guidance is needed on how to provide earlier recognition of drought through the use of different triggers, e.g. high demand or speed of recession indicators. Guidance could be improved to encourage water companies to use average drawdown curves or a range of normal behaviour to identify unusual reservoir behaviour as a drought progresses. These methods should be presented in drought plans.

- Improvements to the current water company understanding of risk factors for resource zone demand–supply balances are needed. Drought planning guidance could be improved to require an assessment of vulnerabilities of resource zones to different types of drought and combined risks, e.g. outage during periods of drought.

- Drought planning guidance on the possible use of temporary licences in place of drought orders is needed. The use of temporary licences is not currently covered in drought planning guidance and the workshops indicated that there is some confusion about their practical uses among the water companies and within the Environment Agency.

Based on the workshops, a number of areas for further research were also identified:

- improved flow forecasting methods including use of medium-range weather predictions;

- how to present and communicate very low probability and high consequence drought events to the public (including the measures needed to maintain essential water supply);

- identifying barriers within water companies to introducing demand–supply measures in a timely manner;

- the development and use of multi-variate triggers;

- environmental needs during severe droughts and the environmental and other consequences of drought;

- modes of failure for different types of water resources systems;

- the link between water resources planning and drought planning (including the use of ‘headroom’ for managing drought);

- testing the drought management planning and management system for groundwater-dominated water resource zones;

- the impacts of climate change on autumn flows;

- the practical use of drought indices for monitoring drought development.

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We wish to acknowledge the guidance and help of the project steering group and those from the Environment Agency, Defra, South West Water and Anglian Water who contributed to this research.

Contents

1 Introduction

1.1 Background

The water resources and drought management plans for England and Wales provide a comprehensive framework for planning future water supplies that addresses economic, social and environmental issues of coping with droughts. However, the recent multi-season drought in south-east England in 2003–2004 to 2006 and prospects of a third dry winter in 2006–2007 raised the issue of how the current drought management framework would cope with severe long droughts resulting from successive dry winters. Furthermore, climate change is expected to alter drought frequency and duration: most global climate models suggest wetter winters and drier summers for the UK, but it is possible that droughts will become more frequent (Vidal and Wade 2008). Ensuring that the drought management system in England and Wales can cope with a wide range of possible droughts will make water supply more robust to future droughts.

1.1.1 Findings of the ‘severe’ droughts project

The ‘severe’ droughts science project undertaken for the Environment Agency in 2006 by a consortium consisting of the Climatic Research Unit (CRU), Centre for Ecology & Hydrology (CEH) and HR Wallingford (Cole and Marsh 2006, Jones et al. 2006a, Wade et al. 2006) demonstrated that large lowland reservoirs such as Grafham in Anglian Water’s supply area were vulnerable to long droughts and that the impact was potentially greater than future climate change. In north-west England, the impacts on water supply were less severe but there were potential environmental impacts that might conflict with the objectives of the Habitats and Water Framework Directives.

The research showed that there were major droughts in the 19th century that were more severe than the ‘design’ droughts currently considered for planning water resources in the UK. The droughts of the 19th century and early 20th century demonstrate the high natural variability of the UK climate and are punctuated with drought episodes that have different characteristics from those of the late 20th century. These major drought episodes could occur again even without climate change and, in some cases, could have greater impacts on water supply and the environment than the most serious droughts of the 20th century.

1.1.2 Consideration of droughts in water company plans

Water companies in England are required to consider a range of droughts in water resources management plans and drought plans. The preparation of both is a statutory duty for water companies, which consult on draft plans and place final plans in the public domain.

As part of their draft water resources management plans consulted upon in 2008, several water companies considered the potential impacts of a third dry winter in 2006 following dry winters in 2004–2005 and 2005–2006, including potential impacts on deployable outputs and the need for applications for drought orders and permits.

Current national guidance developed following the 1997 Water Summit is based on using climate data from 1920 for planning purposes. This provides a good representation of short droughts such as 1921–1922, 1933–1934, 1975–1976 and 1995–1996.

Historical records include several good examples of two-year droughts but very few of longer duration. Some companies have started to explore the sensitivity of their systems to longer droughts and have considered droughts from the 1880 to 1910 period. However, they have focused on the need to plan to maintain permanent supplies rather than temporarily restrict demand or take temporary measures to increase supply during these periods.

1.2 Objectives and purpose of this project

The purpose of this research project is to help the Environment Agency test the current drought management framework against more severe long droughts and future climate change. The project is co-funded by Defra due to its relevance to EU policy initiatives such as:

- the European Commission's Communication on Water Scarcity and Droughts (CEC 2007) which addresses how droughts will be managed in the context of the Water Framework Directive;
- the proposed European Drought Observatory.

The aim of the project was to:

- examine the impacts of long droughts on water supply and the environment;
- test the ability of the existing UK drought framework to manage extreme droughts, including the effects of climate change.

The project explores management measures for maintaining supplies, reducing demand and protecting the environment during long multi-seasonal droughts like those of the early 19th and 20th century.

The project was divided into three stages:

- **Stage 1** – literature review of drought planning and legislation including development of drought metrics for case study systems (and potential regional application) to describe hydrological, water resources and environmental drought;
- **Stage 2** – testing of the current drought management framework (long-term water resources plans, drought plans, drought actions, drought orders, demand restrictions) through interactive workshops using two case studies to elucidate how water companies would manage severe long droughts if they occurred now;
- **Stage 3** – review of the findings from the Stage 1 and 2 studies with the Environment Agency to make recommendations for reinforcing, refining or considering modifications to the current regime.

This final report covers all three stages of the project.

1.2.1 Structure of the report

Section 2 provides an overview of the current drought management framework including legislation, policy, guidance and practical experiences from more recent droughts.

Section 3 describes the selection of two catchments/water supply systems as case studies. These were identified from discussions with the Environment Agency in the initial phases of the project and used for testing the drought management plans to severe drought. The section includes an overview of available data, existing models and the development of simple spreadsheet models for the workshops.

Section 4 looks at definitions and methods for identifying and characterising ‘long droughts’, including various drought metrics. An analysis of historical data (including anecdotal impacts of drought on the environment) used for selecting suitable drought periods for the workshops is presented and a provisional drought selection for the two case studies based on climate and hydrological data is given.

Section 5 describes the testing of the drought management framework through interactive workshops with the Environment Agency, water companies and Defra. Topics covered at these workshops included the resilience of the current drought system to cope with long droughts and evaluation of drought measures.

Section 6 sets out the main findings and recommendations for potential improvements to the drought planning and management system, including additional needs for guidelines and new research.

1.3 Drought definitions

Rainfall or **meteorological** droughts occur due to deficits of effective rainfall (precipitation minus actual evapotranspiration) significantly below long-term averages.

If prolonged, meteorological droughts can develop into the following types of drought (Wilhite and Glantz 1985):

- **Agricultural** droughts with persistently high soil moisture deficits affecting crops;
- **Hydrological** droughts with reductions in river flows and groundwater recharge;
- **Environmental** droughts affecting valued habitats or species;
- **Socio-economic** or **water resources** droughts where the demand for water outstrips supply due to both drought conditions and human activities.

As such, there is no single definition of drought but a series of related concepts relevant to different disciplines, economic sectors and drought durations.[1]

Rainfall or hydrological drought severity can be quantified in statistical terms, but severe ‘agricultural’ or ‘water resources’ droughts are more difficult to define. These occur due to a combination of the intensity and duration of events and the vulnerability of agricultural or water resources systems, including the existing infrastructure, policies and processes and social responses to drought situations.

For the purposes of this study, the following definition of ‘water resources drought’ has been adopted:

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[1] See Wilhite and Glantz (1985) for an original description of drought definitions.

> ‘A shortage of water available to meet ‘normal demands’ (for water supply, industry or the environment) due to a combination of hydrological drought and socio-economic factors affecting water resources systems.’

The multi-faceted nature of drought means that it is difficult to define a ‘severe drought’ and no attempt will be made to provide an exact definition. Rather, ‘major droughts’ are identified due to a combination of meteorological information supported by additional historical evidence.

Sophisticated indicators will not necessarily determine the worst case drought for specific water resources systems as illustrated in the previous ‘severe’ droughts project.

A number of other definitions used to describe drought and water resources systems are given in Table 1.1.

Further definitions of ‘long’ droughts and drought indicators are discussed in Section 4.

Table 1.1 General drought definitions

Term	Definition
Deployable output (DO)	The output of a source or group of sources as constrained by environment, licence conditions, pump capacities, raw water losses, works capacity and water quality considerations. DO is normally reported as the average and critical period deployable output.
Hydrological drought	Changes in the catchment water balance (precipitation, evaporation and storage) leading to deficit of runoff, recharge or low groundwater levels over a specific period. Severity can be classified in a similar way to rainfall drought (see below).
Hydrological yield	The unrestricted output of a source (ignoring licence conditions) and other constraints.
Level of service (LoS)	The standard and reliability of water supply expressed in terms of the frequency of specific drought management measures such as hosepipe bans, restrictions on non-essential use and emergency supplies. The LoS is set by water companies and monitored by Ofwat and the Consumer Council for Water (CCWater). In water resources modelling, a LoS run simulates the behaviour or a system operating according to specific LoS and other system constraints to meet demand.
No restrictions (NR)	A water resources model run that excludes any restrictions on water use in order to determine yield or deployable output (DO).
Rainfall drought	A deficit of rainfall over a specific period significantly below the long term average. The drought severity can be classified used statistical indices such as the Standardised Precipitation Index (SPI).
Water resources drought	A shortage of water available to meet ‘normal’ demands (for water supply, industry or the environment) due to a combination of hydrological drought and socio-economic factors affecting water resources systems.
Worst historic drought (WHD)	The most severe drought on record in terms of its impact on the water resources system. Drought and water resources plans in the UK have typically considered the WHD based on a period from 1920. In some cases, only the period of observed hydrological records (i.e. from the 1950s or 1960s for most UK catchments) is considered.
Yield	The reliable output of a water source considering (current) licence and other specified constraints. In England and Wales, the constraints include a customer level of service. (The constraints considered should be clearly stated when comparing yields between sources, catchments or regions.)
Assessment of hydrological yield	A calculation that finds the maximum average annual demand that can be met by the source subject to specific constraints. Depending on the methodology, yield searches provide a demand that can be met in the worst historic drought or alternatively for a specific return period drought (e.g. 1 in 50 years). In Scotland, the latter method is used to assess hydrological yields of reservoir sources.

2 Existing drought management framework

2.1 Drought legislation and policy

The Department for Environment, Food and Rural Affairs (Defra) deals with water policy issues in England and Wales. Most water resources policy issues in Wales, including the making of drought orders, are now handled by the Welsh Assembly Government.

Three main regulators work with Defra and the Welsh Assembly:

- The Environment Agency is responsible for the management of water resources and protection of the environment. It monitors water companies' performance during a drought to limit damage to the environment.
- The Office of Water Services (Ofwat) oversees the business aspects of the supply and treatment of water to customers.
- The Drinking Water Inspectorate (DWI) monitors the quality of water supplied to customers.

The Water Resources Act 1991 and the Water Act 2003 are the main legislation controlling water abstraction in England and Wales.

The Water Industry Act 1991 details the duties of all water companies, including their obligation to produce a drought plan and their powers to restrict the use of water. The Water Act 2003 amended the Water Industry Act 1991 to insert clauses on water resources and drought planning, and covers all aspects associated with water management in the UK. The legislation requires water companies to carry out stakeholder consultation in the preparation of drought plans.

The management of water resources in the UK is influenced by the Water Framework Directive (WFD). This was introduced in 2000 to consolidate existing legislation and integrate the management of water resources in Europe. The Directive provides a further framework in addition to national legislation to protect the environment and sets the objective of achieving good ecological status for all water bodies. It is the only EU legislation that refers to the management of droughts. Conservation areas identified under the Habitats Directive and Birds Directive (with water-related features) are designated as protected areas under the Water Framework Directive; under the Habitats Directive, 'Natura 2000' sites must be protected such that water-dependent features are not affected by lack of water.

A drought plan should be consistent with the water company's water resources management plans (WRMPs), which make assumptions concerning the frequency of drought management measures. Drought plans should also have regard to the requirements of the Habitats Directive and ensure that drought measures do not impact adversely on designated European protected sites. In future, drought planning will need to be more closely integrated with the river basin management plans (RBMPs) required under the Water Framework Directive.[2]

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[2] http://www.environment-agency.gov.uk/research/planning/33106.aspx

There is a strong inter-relationship between drought planning and water resources planning. It is not possible or desirable (costs, social, environment) to plan water resources infrastructure to maintain normal supplies during rare droughts, therefore drought planning is needed to deal with more extreme events.

Figure 2.1 illustrates the time and geographical scales for the different water management strategies and plans applied in the UK.

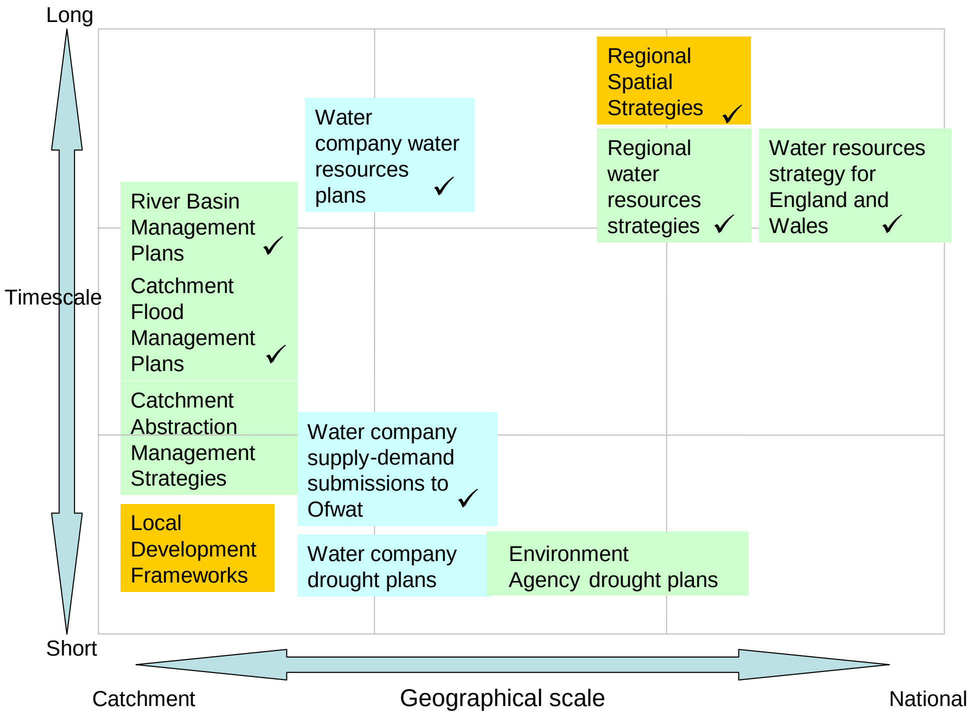

Figure 2.1 Planning activities relevant to water resources and drought management including those that include a consideration of climate change (✓)

(adapted from Environment Agency 2001)

The drought plans and measures used by the Environment Agency and water companies for dealing with droughts are described in more detail in Section 2.2. Detailed summaries of documents reviewed for this study covering drought management and planning are included in Appendix A.

2.2 Drought plans

Water companies have a statutory duty under the Water Industry Act 1991 to produce, consult upon, and maintain drought plans. Drought planning guidance produced by the Environment Agency (Environment Agency 2005) outlines the issues which the plans should consider. The plans should also be produced in accordance with the requirements of the Strategic Environmental Assessment (SEA) Directive 2004. The Environment Agency prepares its own drought plans which describe the actions it will take to detect and manage drought (see Section 2.2.1).

Drought planning forms part of normal operation of water resources and aims to ensure that water companies can continue to supply water during periods of hydrological drought while minimising the potential environmental impacts of drought measures.

As rainfall deficits develop and water resources become depleted, drought actions are triggered sequentially in order to convene drought management teams, conserve supplies and initiate publicity campaigns.

As a drought becomes more serious, the Water Resources Act 1991 (as amended by the Environment Act 1995 and the Water Act 2003) allows for three mechanisms for dealing with drought situations – ordinary drought orders, emergency drought orders and drought permits (see Section 2.2.3).

Drought plans are about managing climate variability. The plans are updated every three years (the latest were published in 2007–2008), and involve short-term actions rather than influencing long-term investment strategy. Thus the plans can evolve alongside climate change or long multi-seasonal droughts, and actions can be adapted to changes in drought conditions.

The main features of water company drought plans are that they should include:

- measures to restrain the demand for water;
- measures to obtain additional water resources;
- monitoring activity to understand the impacts of drought and the effectiveness of drought management measures;
- management arrangements, including requirements for approvals and permits and liaison with key stakeholders;
- mitigation activities to minimise the impacts of drought measures on the environment.

The drought plans produced by the Environment Agency and water companies are described in more detail in Sections 2.2.1 and 2.2.2 respectively.

2.2.1 Environment Agency drought plans

The Environment Agency drought plans cover each of its areas in England and Wales. There are also larger regional plans and a plan detailing how management of droughts will be implemented throughout England and Wales. Altogether there are 32 drought plans (Environment Agency 2007). The plans describe:

- the actions the Environment Agency will take to reduce the effects of the drought on water users;
- management procedures;
- the Environment Agency’s role in issuing drought order and permits;
- how the Environment Agency will deal with applications for drought orders and permits.

The Environment Agency reviews its drought plans every three years.

The drought management teams set up at both area and regional level include representatives from all relevant Environment Agency functions to ensure that drought management is co-ordinated. Meetings are normally held at least once per month during a drought, though the frequency may vary depending on the nature of the event.

Representatives of the regional drought management team undertake regular liaison meetings with water companies to ensure that drought measures are co-ordinated and that appropriate opportunities for putting across joint messages to the public are maximised.

Regional plans

The requirement for regional drought plans arose from the Environment Agency's close involvement in water company drought plans and the findings of an internal audit of drought management.

The regional plans detail actions to be taken during a drought and how drought development will be recognised using environmental data from the various catchments. The main aim is to present a structured framework for drought management while maintaining the level of flexibility necessary to respond to different types of droughts.

The regional plans set out:

- drought monitoring arrangements, including appropriate hydrological and environmental triggers;
- drought management actions.

As an example, Table 2.1 lists drought management actions from Thames Region's drought plan.

Table 2.1 Actions undertaken during each drought stage (reproduced from Thames Region's drought plan)

Drought stage	Action
Non drought	• Complete/progress actions identified in drought plan. • Monitor observed hydrological data against generalised environmental trigger (GET) levels. • Monitor observed environmental data against water company triggers. • Review baseline data collected.
Drought	• Commence meetings of regional and area drought management teams. • Start drought reporting. • Identify specific, key PR actions to take. • Increase environmental surveillance as appropriate. • Initiate Regional Drought Co-ordination Group meetings with water companies, Ofwat, Natural England, British Waterways, Council for the Protection of Rural England (CPRE), National Farmers' Union, Port of London Authority, local authorities, Wildlife Trusts and local pressure groups as required. • Assess drought order / drought permit applications and identify environmental protection / implementation actions.
Post drought	• Undertake post event review – identify areas of weakness. • Complete post drought report containing analysis of data collected to assess the environmental impact of the drought and evaluate the effects of mitigation measures. • Revise regional drought plan. • Evaluate/agree revisions to water company drought plans.

2.2.2 Water company drought plans

Water companies had previously submitted drought plans to the Environment Agency. The process is now statutory and the plans are subject to consultation and to changes by the Secretary of State/Welsh Ministers.

Drought plans detail how a water company will meet water supply requirements during a drought without too much reliance on drought permits or drought orders (Environment Agency 2005). They are also required to avoid any detriment to the environment where possible. The key questions that must be addressed in the drought plan are:

- What demand-side management measures might need to be implemented by the water company?
- What supply-side measures might need to be implemented by the water company?
- How will the effects of the drought and management measures implemented be monitored?

There are a number of steps in the drought plan process including consultation with a variety of parties (e.g. Secretary of State/Welsh Ministers, the Environment Agency, Ofwat and licensed water suppliers) before the final plan is published. The requirements of plans are set out in the Drought Plan Direction 2005;[3] Table 2.2 details on how these may be met.

Recent drought plans for all water companies address each of the requirements in Table 2.2 but exhibit some differences in presentation, terminology and level of detail. This is illustrated in the water company drought plans by Anglian Water and South West Water described in Sections 3.1 and 3.2.

Table 2.2 Main features of water company drought plans [1]

Features	**Details**
Management plan detailing each stage and when these should be implemented	This includes details of the possible actions to be taken during the drought and as it recedes. These actions correspond to the severity of the drought, e.g. at what stage drought management should be implemented once a trigger is reached.
Number of different possible scenarios	These include different ranges of dry summers and winters as well as multi-season droughts. This will improve the water company's resilience to a number of possible drought situations and therefore improve management planning. It must give reasons for choosing these scenarios.
Consider potential impacts on the environment of the area	The water company will need to monitor the environment, highlighting any designated areas of ecological importance such as any sites designated under the Habitats Directive. Environmental factors, which could be affected by any drought measures set out in the plan, should be detailed at these sites individually to determine if there are any environmental implications. This could be achieved through the use of the Environment Agency's monitoring data records as well as consultation with Natural England or the Countryside Council for Wales (CCW). Mitigation measures should be in place in cases where there could be impacts on water or the environment as a result of the drought plan.
Communication strategy	This sets out how the water company will provide information to its customers through its communication strategy, e.g. when and in what way information will be provided during a drought.
Actions to be taken following the drought	These must be addressed and, if it is necessary to review the plan, it should be updated.

Notes [1] Adapted from Environment Agency (2005)

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[3] http://www.defra.gov.uk/environment/quality/water/resources/documents/plan0510.pdf

2.2.3 Drought orders and permits

Drought orders and permits can be granted under the Water Resources Act 1991, as amended by the Environment Act 1995 and the Water Act 2003. The available types are:

- drought permits;
- ordinary drought orders;
- emergency drought orders.

Drought permits are granted to water companies by the Environment Agency, while ordinary drought orders and emergency drought orders are made in England by the Secretary of State or in Wales by Welsh Minsters. Further details are given in Table 2.3.

Guidance and instructions on applying for drought permits and orders are provided by Defra (Defra 2005). Under a drought order, powers can be granted to:

- water companies to reduce demand and increase supplies;
- the Environment Agency for protecting the environment from abstraction.

Drought orders and permits may be granted to water companies if an exceptional shortage of rain threatens to lead to a serious deficiency of water supply. The water company will be expected to have implemented demand management measures in accordance with the associated impacts on the environment, although this is not a statutory requirement (Environment Agency 2005). Such measures include public campaigns to reduce the use of water, hosepipe bans and leakage control. Water companies have powers to impose hosepipe bans if they need to without requiring a drought order. The Drought Direction 1991[4] specifies the different non-essential uses that can only be restricted when a non-essential use drought order is granted.

The Environment Agency takes other water uses into account when granting drought permits or supporting drought orders. Potential drought permits must be considered in a drought plan otherwise it is unlikely they will be granted. Drought orders must also be considered in the plan otherwise the application will not usually be supported by the Environment Agency.

To ensure minimum damage to the environment, consideration should be given to:

- location;
- mitigation of impacts;
- when the measures should be implemented.

For example, winter drought permits are normally preferred by the Environment Agency since they can help to monitor and replenish resources as well as reducing the likelihood of the need for drought orders or permits during the summer (Defra 2005).

There are a number of steps involved in applying for a drought order or drought permit, which requires a lot of preparation. These include:

- early contact with the Environment Agency, Defra, Welsh Assembly Government, Natural England and Countryside Council for Wales;
- submission of environmental reports along with the application.

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[4] http://www.defra.gov.uk/environment/quality/water/resources/documents/droughtdirection1991.pdf

Table 2.3 Differences between drought permits, drought orders and emergency drought orders [1]

Type	Description	Details
Drought permit	• Water can be taken from specified sources by water undertaker. • Modify or suspend restrictions or obligations to which that undertaker is subject relating to the (existing) taking of water from any source.	• Granted by the Environment Agency. • Duration: can last up to six months, though this can be amended and extended up to a year.
Drought order	Further to drought permits: • deal with discharges of water, abstractions and discharges by people other than the undertaker affected; • deal with supply, filtration and treatment obligations; • authorise access to other's land (e.g. to lay water transfer pipes); • water undertakers can prohibit or limit particular uses of water.	• Made in England by the Secretary of State and in Wales by Welsh Ministers. • Duration: can last up to six months, though this can be amended and extended up to a year.
Emergency drought order	Further to drought orders: • the water undertaker has complete discretion on the uses of water that can be prohibited or limited; • the water undertaker can authorise supply by standpipes or water tanks.	• Granted in England by the Secretary of State and in Wales Welsh Ministers. • Duration: three months and can be extended to five months.

Notes [1] Adapted from Defra (2005)

2.3 Experiences from recent droughts

The existing drought framework was last tested during the multi-seasonal drought in 2004–2006 in south-east England. The drought was one of the worst in the last 100 years and, based on drought indicators, assessed to be a very severe albeit not exceptional drought (Environment Agency 2008). The drought of 1976 remains the most intense in the past 50 years; however, the 2004–2006 drought lasted longer than both the 1989–1990 and 1997–1998 events.

The summary report of the 2004–2006 drought produced by the Environment Agency in August 2008 and hydrological prospect reports published by the Environment Agency during the drought (Environment Agency 2006a,b,c) indicate there is evidence that the existing drought management system was instrumental in reducing the impacts of the drought on water resources and the environment. The Environment Agency and water companies monitored the development of the situation closely, adhering to their drought plans and implementing lessons learned from previous events.

In accordance with the Environment Agency's drought plans, drought management teams were formed and meet regularly to appraise the situation. Once critical thresholds were reached, the groups were in close contact with the water companies, other abstractors and Defra, keeping the most important water users informed of the situation. The Environment Agency produced overview reports at regional and national level, including recommendations for actions for the water companies every three months from February 2006 to August 2006. A number of other actions were taken or considered by the Environment Agency during the drought. Specific actions included:

- A number of press releases were issued to raise awareness of the issues and inform the public of the progression of the drought. Weekly reporting was published on the internet. The water companies worked closely with the Environment Agency in publicity campaigns.

- A new drought permit was issued to Sutton and East Surrey Water to allow pumping into Bough Beech reservoir until the end of May 2006. Two drought permits already in force (Bewl and Hardham) were extended.
- Formal restrictions on 600 spray irrigation licences were introduced in collaboration with the farmers.
- A number of actions for the water companies were recommended.

The water companies largely followed the recommendations from the Environment Agency.

- Most water companies in the south-east introduced and maintained hosepipe bans from February 2006 to January 2007, affecting 13 million people.
- Publicity campaigns were conducted to encourage the saving of water.
- Three companies (Sutton and East Surrey Water, Mid-Kent Water and Southern Water) applied for and enforced drought orders for non-essential use. Thames Water applied for a normal drought order for London to the Secretary of State but this was withdrawn in August as conditions improved (Thames Water 2006).
- Leakage control was improved, although complaints from gardeners and other trades were received suggesting mismanagement by the water companies.
- Old groundwater boreholes were brought into use by some water companies to ensure supply.

Overall it was assessed that the measures put in place improved the situation in 2006 considerably. Hosepipe bans, as well as appeals to save water, have been assessed by water companies to have reduced customers' demand for water by 5–15 per cent. Supply was also increased by drought permits, improved leakage control and use of old boreholes.

The reduction in demand across the south indicates some confusion about where the hosepipe bans actually applied. Towards the end of the summer, concerns were also raised that another dry winter would cause severe restrictions the following summer. Hosepipe bans were therefore kept in place until January 2007. The hosepipe bans attracted negative comments from gardeners in particular, who argued that they were suffering disproportionately from these restrictions. The volume of water saved by hosepipe bans was compared unfavourably with the volume of leakage from water companies' own pipes. Some discontent about insufficient leakage control was raised by a number of groups, who felt the impacts of hosepipe bans and non-essential use bans on their businesses were disproportionate.

The lessons learned during the drought of 2004–2006 have led to a number of suggestions for improvements to the framework.

In particular, the drought highlighted significant inconsistencies in restrictions on water use imposed by different water companies and led to a call for modernisation of the scope of hosepipe ban powers. The existing powers apply only to watering private gardens and washing private motor cars. However, there are more water-hungry uses in the domestic sector than there were decades ago when these powers were introduced.

It is essential that the hosepipe legislation and its application by water companies are clear and unambiguous. The two main changes currently under consideration are:

- modernisation of the hosepipe ban including non-essential use (Waterwise 2006);
- development of a water industry code of practice governing demand restrictions.

A consultation document (October 2007) is available on the Defra website[5] and the Government may use an opportunity in Parliament to legislate to bring the new discretionary use ban powers into effect.

A draft Flood and Water Management Bill was published on Defra's website on 21 April 2009 for consultation (see Section 2.4). It is currently unclear when the changes to legislation will be introduced but the consultation period ended on 24 July 2009.

2.4 Evaluation of current drought alert and management system

Overall the current approaches to drought planning in the UK provide adequate means for dealing with natural climate variability. Despite the two notable drought periods in 2003 and 2004–2006, there have not been shortages of public water supply over the last decade.

The complexity of water company plans are variable; some companies have well-developed drought curves to define drought actions and modelling systems to forecast drought, while others have simpler systems of triggers and rules for maintaining water supply.

The Environment Agency's hydrological and drought reporting has improved significantly with information posted on its website. Reporting is under continuous improvement to provide hydrological information in a consistent format across the country.

2.4.1 Lessons from the 2004–2006 drought

Based on the experiences from the 2004–2006 event, a report to Defra by Waterwise (Waterwise 2006) identified a number of limitations and inconsistencies in the application of the current drought framework by the water companies:

- **Lack of clarity about the stages of drought planning and corresponding actions.** The stages/level or steps vary between water companies and there is particular confusion about the stage at which hosepipe bans are introduced.
- **Confusion over the allowed and disallowed activities during a hosepipe ban as to why certain activities are permitted and others not.** Large differences in allowed activities were recorded during the drought in 2004–2006.
- **Lack of flexibility for improvements in technology.** Restrictions apply to all irrigation systems, although some are more water efficient than others.

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[5] http://www.defra.gov.uk/environment/quality/water/resources/documents/consultation-2007.pdf

- **Lack of concessions.** No concessions to elderly/disabled people are currently included.
- **Lack of consistency between companies allowing different interpretations, which is confusing to consumers.** Advice and communication of drought and hosepipe bans are inconsistent, especially between different water companies.

Some of these limitations may be addressed in new legislation. The draft Flood and Water Management Bill published in April 2009 includes provisions to enable the Secretary of State and Welsh Ministers to extend the hosepipe ban powers of water companies; this will enable them to ban a wider range of discretionary uses of water. Under the draft Bill, uses of water not currently covered by the hosepipe ban (e.g. filling private swimming pools and cleaning patios) would be added to the legislation through an Order approved by Parliament and the National Assembly for Wales (supported by an impact assessment of costs and benefits).

The widening of the scope of bans is intended to enhance the ability of water companies to manage demand in times of shortage, particularly in the early stages of a drought. The proposed legislation is flexible, allowing water companies to apply different restrictions or prohibitions as needed for different areas, different groups of customers and excluding particular apparatus (e.g. hosepipes). In addition, a requirement to publish a notice in at least two local newspapers and on the company's website is proposed. To maintain flexibility, a standard notice period is not currently proposed but the period should be short and it will be left to the courts to decide whether sufficient notice has been given in any particular case.

Although the water industry is now more resilient to drought stress, there is the question of whether it would be able to cope with long drought conditions should they occur (Marsh et al. 2007a). While the drought plans consider multi-seasonal drought scenarios, these are based on more recent droughts (2004–2006) or other historical droughts back to 1920 which may be less severe than those from the turn of the 19th and 20th centuries. Moreover, the performance of the drought framework has not been tested on a real long drought with three dry winters.

3 Selection of case studies and models

Two case studies, Grafham in the Environment Agency's Anglian Region and Wimbleball in its South West Region, were selected to test the drought framework under more severe drought conditions than currently considered in water company drought planning.

The selection was based on the following criteria:

- sites that demonstrate different hydrological characteristics and consequently different characteristic responses to long drought conditions;
- inclusion of water resource zones with reservoirs with a different balance of pumped storage versus natural inflows, and both surface and groundwater resources;
- the availability of good hydrological data and models to link long-term historic climate series and climate change scenarios to changes in yield;
- collaboration with water companies in order to explore management responses in the event of severe long droughts.

Grafham was included in previous Environment Agency research on severe droughts (Cole and March 2006, Jones et al. 2006a, Wade et al. 2006). This case study builds directly on the previous work with a new focus on drought management responses.

Similarly, Wimbleball was subject to a previous Environment Agency and University of Oxford research project that considered the impacts of probabilistic climate change scenarios on future reservoir yield and likelihood of reservoir failure (Lopez et al. 2008). This case study uses different hydrological and water resources models, and hindcasts the modelling back to the 1860s to examine the impacts of long droughts and management responses.

While both these case studies include reservoirs in the south of England, they exhibit distinct differences:

- Grafham is located in the one of the driest parts of the UK, with an annual precipitation of approximately 600 mm, high evaporation losses in summer months and low annual runoff.
- Wimbleball is situated within the Exe river catchment, which has more than twice as much precipitation and is dominated by surface water. Surface water runoff is around eight times higher than for the Ouse (Table 3.1).

Grafham has a net storage volume of 52,867 million litres (Ml), more than twice the size of Wimbleball at 21,230 Ml.

Further background and details of each case study, including available data and water resources models, are provided in Sections 3.1 and 3.2 respectively.

Table 3.1 Characteristics of the two case study areas

(a) Catchment water balance

Catchment	Water balance [1]			
	BFI	**Average precipitation (mm)**	**Average losses (mm)**	**Average annual runoff (mm)**
River Ouse at Denver Complex	74%	601	498	103
River Exe at Thorverton	51%	1295	451	844

Notes [1] Marsh and Hannaford (2008)

(b) Synthetic flows available

River	Flow gauge	Gauge no.	Catchment area (km^2)	Maximum elevation (m)	Q95 (m^3/s)	Q10 (m^3/s)
Ely Ouse	Denver complex (1865-2002) (1801-2002)	33035	3,430	167	0	29
Exe	Thorverton (1865-2002)	45001	601	519	2	39

(c) Water resources models

Main reservoir	Abstraction points/inflows	Reservoir water resources models
Grafham	Rivers Ouse and reservoir inflow	Grafham OSAY model Grafham spreadsheet model (improved for this study)
Wimbleball	Natural inflow Exe, Exebridge pumped storage	Wimbleball (including Clatworthy and other sources) LancMod water resources model Miser water resources model Wimbleball spreadsheet model (developed for this study)

3.1 Anglian Water – Grafham

Grafham reservoir abstracts water from the River Ouse at the Offord intake above a prescribed minimum residual flow or hands-off flow. The reservoir has a very small natural catchment area and limited natural inflow, and relies on river abstraction throughout the year. The reservoir is used for direct public water supply passing through Grafham Water Treatment Works (WTW).

A schematic of the system is shown in Figure 3.1; crucial reservoir parameters including minimum residual flow (MRF) and compensation flow are included in Table 3.2.

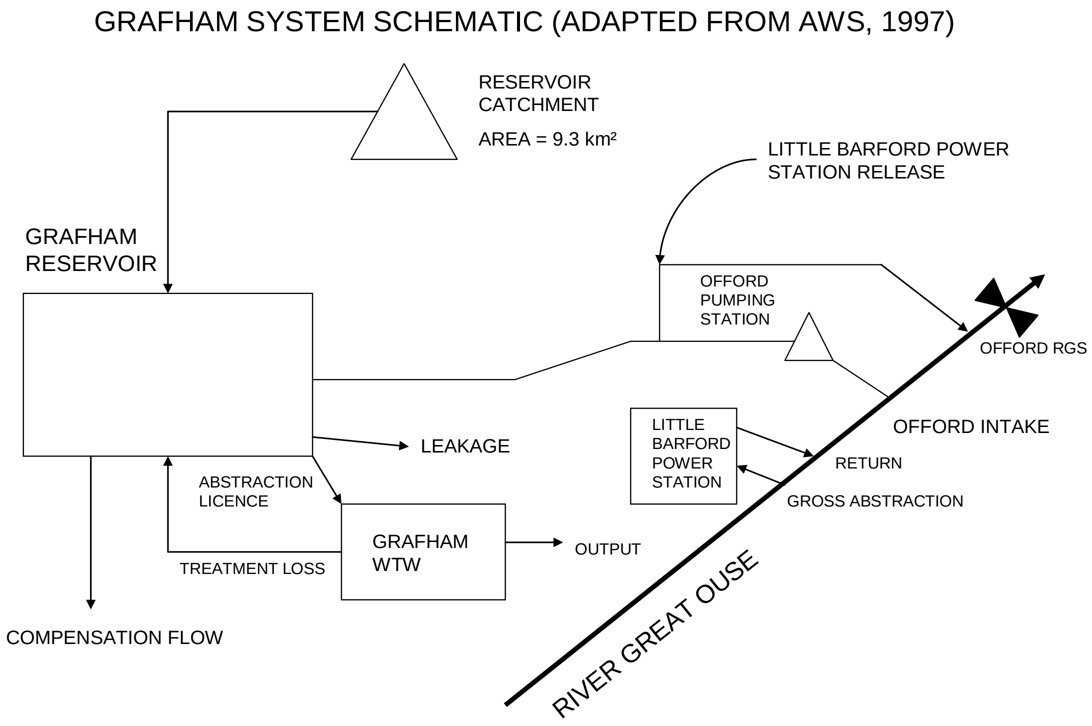

Figure 3.1 Schematic of the water resources system for Grafham reservoir

Table 3.2 Licence and prescribed flows for Grafham reservoir

Licences	Daily (Ml/day)	Annual (Ml)	Additional comments
Offord Pumping Station (PS)	485		MRF = 136 + 0.25 (Flow-136) Ml/d at Offord River Gauging Station (RGS)
Compensation flow			5.5 Ml/day

3.1.1 Anglian Water's drought plan

Drought planning for Grafham reservoir is covered in Anglian Water's drought plan, which includes detailed information set out in tables of actions during normal, potential drought and drought conditions. The move from normal to drought conditions is determined by trigger levels that include triggers for surface water reservoirs (reservoir levels) and groundwater sources (deepest advisable pumping water levels).

Due to the variability of droughts in terms of intensity, duration, areal extent and response of individual sources to drought, Anglian Water does not make use of regional or water resource zone (WRZ) triggers. Restrictions on demand are triggered using individual reservoir control curves. Trigger curves are developed based on different historical drought scenarios from 1920–1997.

The four principal triggers – a Drought Alert Curve and three drought triggers associated with levels of service (LoS) – are listed in Table 3.3 alongside associated actions. The trigger curves in Figure 3.2 are examples for illustration and not the actual triggers used for Grafham.

Table 3.3 Summary of reservoir drought management curves

Drought Management Curve	**Action**	**Frequency of measures (years)**
Drought Alert Curve	Signal that reservoir storage is approaching the level where Anglian Water would increase public awareness of the need to conserve water and consider imposing demand restrictions. Initiate liaison within Anglian Water and between Anglian Water and the Environment Agency to mobilise resources for future action.	n/a
Upper Trigger Curve – LoS 1	Publicity; enact restrictions on use of hosepipes	1:10
Mid Trigger Curve – LoS 2	Publicity; enact restrictions on non-essential use and Drought Permit / Order to reduce the minimum residual flow at the river appropriate (not included for Alton, Ardleigh and Covenham)	1:40
Lower Trigger Curve – LoS 3	Enact standpipes and rota cuts	1:100

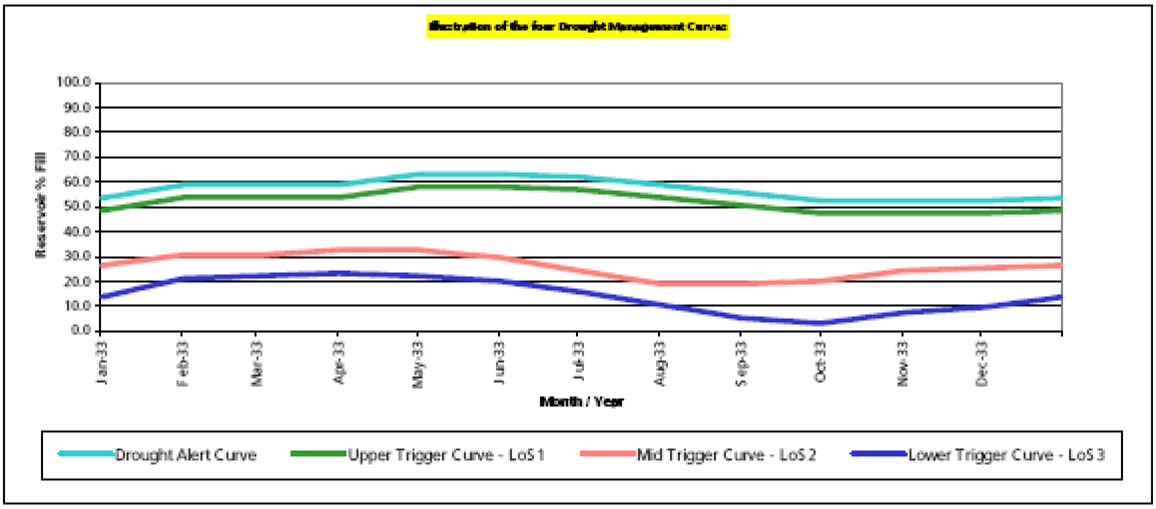

Figure 3.2 Example of drought trigger curves

3.1.2 Available climate and hydrological data

Historical climate data and other hydrological data were collated for developing drought scenarios and simple reservoir models for use in a workshop setting. The following data are available for Grafham:

- Anglian Water's naturalised river flows from 1920–2002 based on outputs of the Stanford Watershed Model (SWM);
- extended rainfall records and reconstructed river flows from the 'severe' droughts project for the period 1801–2004 (Jones et al. 2006a);
- gauged river flow records for the period 1980–2002 for Denver sluice and Offord from the National Water Archive (NWA);[6]

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[6] Denver's NWA record is patchy and incomplete. Further data are needed from the Environment Agency to complete the record.

- reservoir, abstraction and demand characteristics suitable for detailed ‘behavioural modelling’ of the reservoir and/or water resources zone.

Other hydrological data such as spring flows and groundwater levels were also collated.

Available anecdotal evidence of the impacts of historical droughts on the environment in Anglian Region was examined and is described in more detail in Section 4.4.

Anglian Water was consulted to gather the latest thoughts on likely demand reductions during drought conditions and other information that supports its drought plan. This information was used mainly when preparing to test the drought management system in a workshop setting described in Section 5.

3.1.3 Water resources modelling

Water resources modelling forms the basis for simulating the impacts of drought conditions on water resources and the effects of introducing various demand and supply measures as a drought develops. For Grafham reservoir, two different water resources models were available:

- Anglian Water’s in-house, Windows-based OSAY (Operating Strategies method Assessing Yield) model;
- a simple Microsoft® Excel model developed by Wade et al. (2006).

Anglian Water uses OSAY for water resources management and planning for Grafham reservoir. The model calculates the water balance of the reservoir based on river flows, licence conditions, pump capacities, reservoir characteristics and target level of service. Although it is a resource optimisation model, it can also be used for behavioural modelling. For ‘no restrictions’ runs, OSAY works by running the water balance (subject to the above constraints) and increasing the demand for the water until the reservoir is empty or reaches a defined level to estimate the average deployable output (ADO) for the worst historical drought (WHD).

This estimate is very sensitive to the length of record. For ‘levels of service’ runs, OSAY searches for a demand that can be met when demand restrictions are put in place. The level of service ADO will be higher than the ‘no restrictions’ ADO because using restrictions will reduce the drawdown of the reservoir and prevent it from failing during the drought period. Details of the OSAY model are given in an Anglian Water Services (AWS) document (AWS and Mott MacDonald 1997) and notes provided by the software developer (Page, personal communication).

The simpler spreadsheet model for Grafham was developed by mimicking the behaviour of OSAY in order to be able to assess the effects of longer historical droughts on water resources. It was shown that this model produced almost identical results to OSAY. This model was selected for use in this study due to:

- the simplicity of the spreadsheet modelling tool;
- the need to make changes to the model to allow for drought management decisions to be considered interactively in workshops.

The main changes made to the original model for the study include:

- converting from a daily to a monthly time step in order to be able to step through a drought situation more quickly;
- incorporation of various drought measures affecting demand and supply;

- general presentation of the results showing trigger curves and demand deficits.

The original water resources spreadsheet model for Grafham is described in Appendix 2 of Part 3 of Wade et al. (2006). The modified version used in this study is described in further detail in Appendix D. An overview of drought measures taken from the drought management plan is also included in Appendix D.

The use of groundwater modelling tools to test the impact of drought conditions and drought management for both surface water and groundwater sources within the Ruthamford Water Resource Zone was also considered for this study. However, time pressures and the need to keep the modelling relatively simple for practical reasons for the workshops meant that detailed groundwater modelling was not feasible. Groundwater sources were, however, considered in the assessment as potential additional supplies and the impacts of droughts on groundwater sources were considered in a qualitative way. The methodology used for testing the drought management framework is described in detail in Section 5.1.

3.2 South West Water – Wimbleball

Wimbleball reservoir on Exmoor was completed in 1979. The dam impounds water from the River Haddeo to form a reservoir with a net storage of 21,320 Ml and supplies Exeter and parts of east Devon by releasing water into the River Exe. This water is subsequently abstracted at Tiverton and Exeter. Water is also supplied by pipeline to Wessex Water's Maundown Water Treatment Works.

Wimbleball is the primary resource in the Wimbleball strategic supply area (SSA) and is used to augment the River Exe for subsequent abstraction at Bolham Weir and Northbridge. Within this strategic area, sandstone groundwater sources in the southern part of the Otter valley are also used for public water supply. A schematic of the system is included in Figure 3.3 and details of the system are given in Table 3.4.

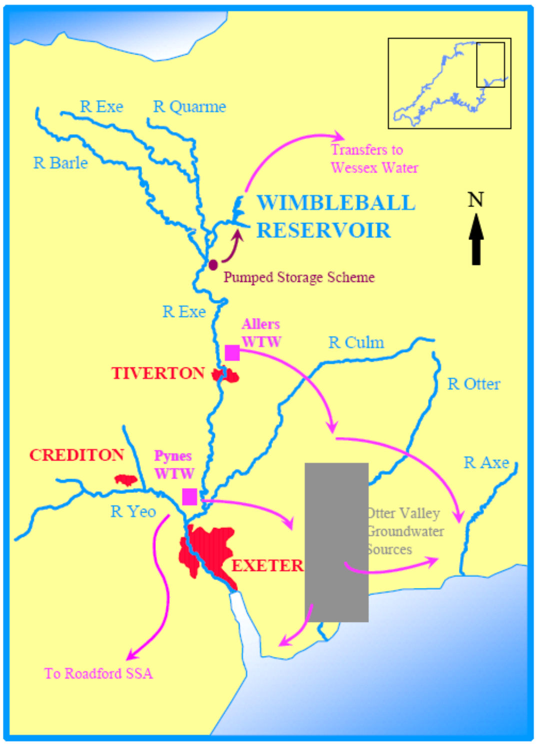


Figure 3.3 Wimbleball strategic supply area (South West Water 2007)

Table 3.4 Licences and prescribed flows for Wimbleball reservoir

Licences	Daily (Ml/day)	Annual (Ml)	Additional comments
Wimbleball PS	150	13,633 (Jan–Dec)	Abstraction between 1 November and 31 March only Prescribed flow = 1.16 m^3/s, 50% take Annual fisheries bank = 900 Ml No abstractions for pumping station at the same time as making releases from Wimbleball Maximum abstraction rate of 135 Ml/d (operational contingencies)
Wimbleball release		12,585	
River Exe at Northbridge Licence of Right (for Pynes WTW, Exeter)	24.457	8,926.8	Licence of Right
River Exe at Northbridge (for Pynes WTW, Exeter)	42	14,300	Prescribed flow = 3.16 m^3/s at Thorverton ground station (GS) (based on Thorverton natural flow)
River Exe at Bolham (for Allers WTW, Tiverton)	32	11,564.5	When the natural flow in the River Exe at Thorverton is 3.16 m^3/s or less, abstraction is restricted to 2.7 Ml/d excluding water discharged from Wimbleball to the river for public water supply abstraction.

3.2.1 South West Water's drought plan

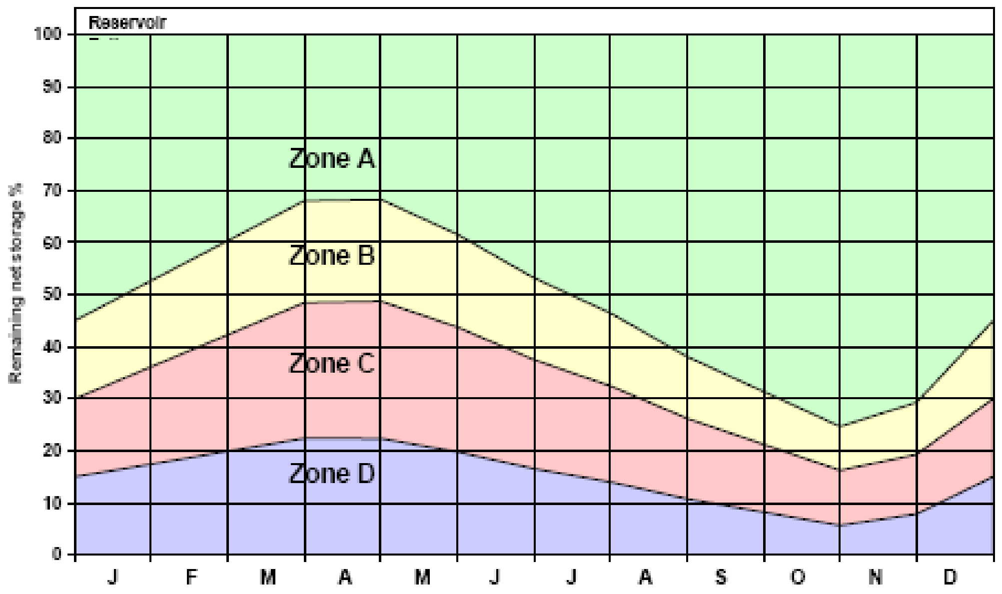
Like Anglian Water's drought plan, South West Water's drought plan is based on drought management curves for its three strategic supply areas. However, a slightly different terminology is used to describe the 'trigger' curves. South West Water distinguishes between local and strategic reservoirs which have different storage zones related to level of service, with three zones (A–C) for local reservoirs and four zones (A–D) for strategic reservoirs.

The company's strategy in the management of its water resources is to first use local sources of water before strategic reservoirs. Zone D actions, which include bans on non-essential use of water and further supply enhancement drought orders, are only triggered by strategic reservoirs. The trigger curves were developed theoretically and then refined based on different historical droughts.

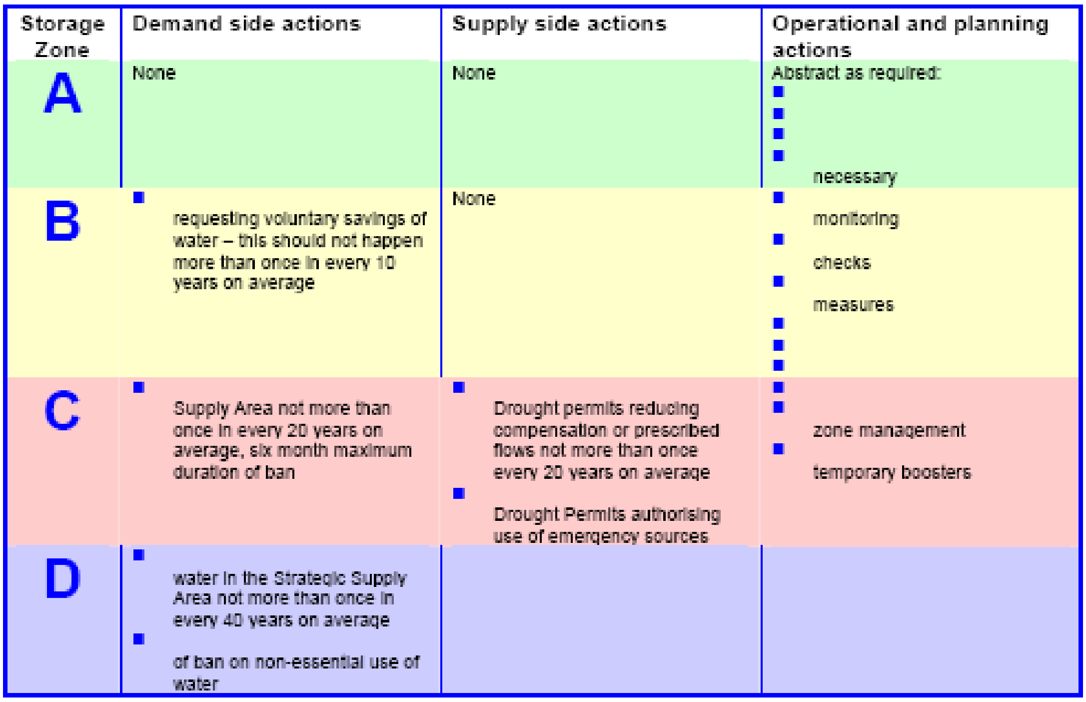
Figures 3.4 and 3.5 provide illustrations of the drought management curves including zones and associated actions. In terms of actions taken during different stages of a drought, these seem to differ somewhat from those used by Anglian Water.

With regard to past drought events, the drought plan states that a number of drought orders previously used in 1995 have associated schedules and monitoring agreed with the Environment Agency. However, no specific information on these drought orders has been included in the plan.

Typical drought management zones



Actions taken when storage enters the zones



Storage Zone	Demand side actions	Supply side actions	Operational and planning actions
A	None	None	Abstract as required: ■ ■ ■ ■ necessary
B	■ requesting voluntary savings of water – this should not happen more than once in every 10 years on average	None	■ monitoring ■ checks ■ measures ■ ■ ■
C	■ Supply Area not more than once in every 20 years on average, six month maximum duration of ban	■ Drought permits reducing compensation or prescribed flows not more than once every 20 years on average ■ Drought Permits authorising use of emergency sources	■ ■ zone management ■ temporary boosters
D	■ water in the Strategic Supply Area not more than once in every 40 years on average ■ of ban on non-essential use of water		

Figure 3.4 Summary of reservoir drought management curves

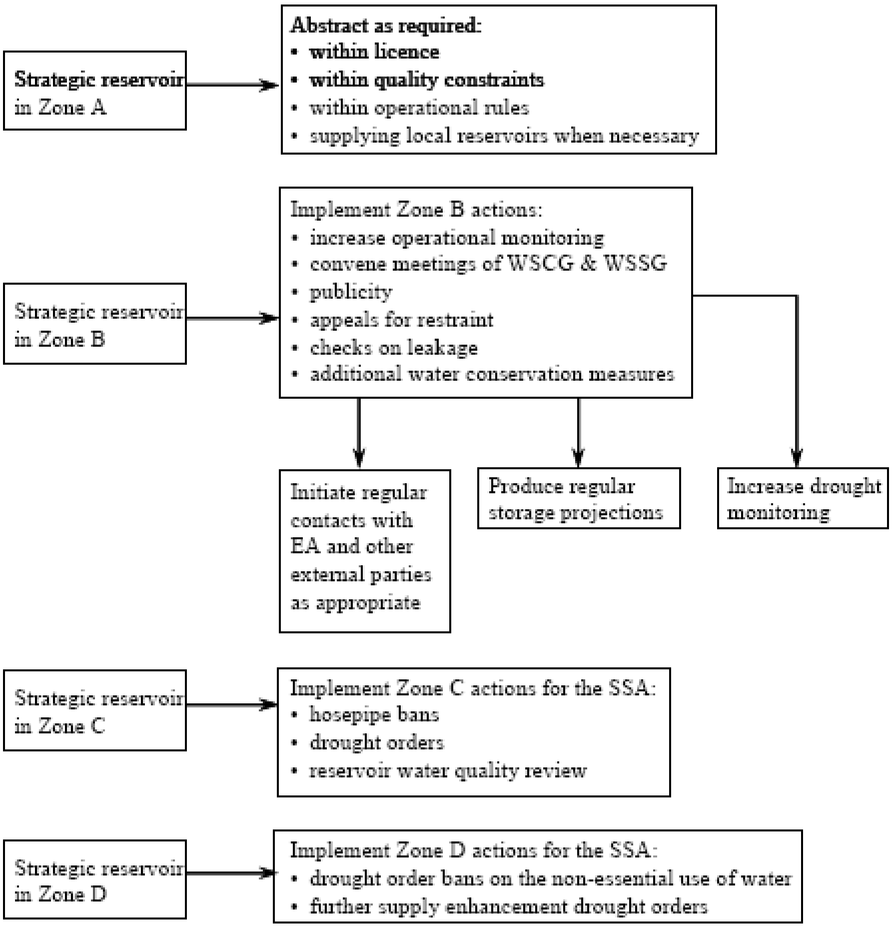


Figure 3.5 Actions for different zones for strategic reservoirs

3.2.2 Available data

Historical climate data and other hydrological data were collated for developing drought scenarios and simple reservoir models for use in the workshops. The following data are available for the Wimbleball SSA:

- reconstructed river flows from 1865 from Jones et al. (2006b);
- naturalised river flows for Exebridge, Wimbleball and Thorverton for 1955–2006 provided by South West Water;
- reservoir, abstraction and demand characteristics suitable for detailed ‘behavioural modelling’ of the reservoir and/or water resources zone

Other hydrological data such as spring flows and groundwater levels were also collated. Available anecdotal evidence of the impacts of historical droughts on the environment was also examined and is described in further detail in Section 4.4.

South West Water was consulted to gather the latest thoughts on likely demand reductions during drought conditions and other information that supports the drought plan. This information was used mainly in preparations to test the drought management system in a workshop setting as described in Section 5.

3.2.3 Water resources models

For the Wimbleball SSA, several different modelling systems have been used by South West Water to simulate the impacts of drought conditions on water resources and the effects of introducing various demand and supply measures.

South West Water currently uses the commercial model ‘Miser’ for undertaking water resources modelling for Wimbleball. Miser is a modelling system that can simulate system behaviour, maximise conjunctive yield, safeguard supplies and minimise cost. A LancMod model developed by the Environment Agency is also available for the Wimbleball SSA, although this model has not yet been validated or compared against South West Water’s model. Both models are fairly complex conjunctive use models, which include a number of additional reservoirs located within the Wimbleball SSA and groundwater sources used for supply.

The models were not appropriate for this research study – partly due to their complexity and partly due to the type of software used, which would not be suitable for practical application in a workshop setting. It was therefore decided to develop a simple monthly spreadsheet model similar to that developed for Grafham, which would be limited to covering the supply–demand balance for Wimbleball reservoir. Like the Grafham model, it incorporates various drought measures affecting demand and supply and presents the results showing trigger curves, drought actions and demand deficits.

The different licences and uses of water from Wimbleball are illustrated in Figure 3.6 and the simple spreadsheet model is described in detail in Appendix E. The modelled historical drawdown results were checked against the Miser results by South West Water with reasonably good agreement. A daily model was also developed for 1975–1976 in order to examine the level of smoothing which occurs due to the use of a monthly time step. It was found that reservoir levels do not drop as steeply in the monthly model due to smoothing of flows and because abstraction for fish farming in July and August is spread out over a full month rather than over a few days. Overall the model was considered suitably detailed for testing the drought framework.

Because the model covers only part of the water resource zone and excludes groundwater sources, it was difficult to check the demand figure used as input for the model against reported water company figures. In order to replicate reservoir drawdown more accurately during severe drought conditions (especially during the summer months when fish bank abstraction is taking place), the water resources model has been set up to run using a higher than normal demand (150–155 Ml/day). This produces a drawdown close to that observed using daily data and reflects the likelihood of increased baseline demand during droughts.

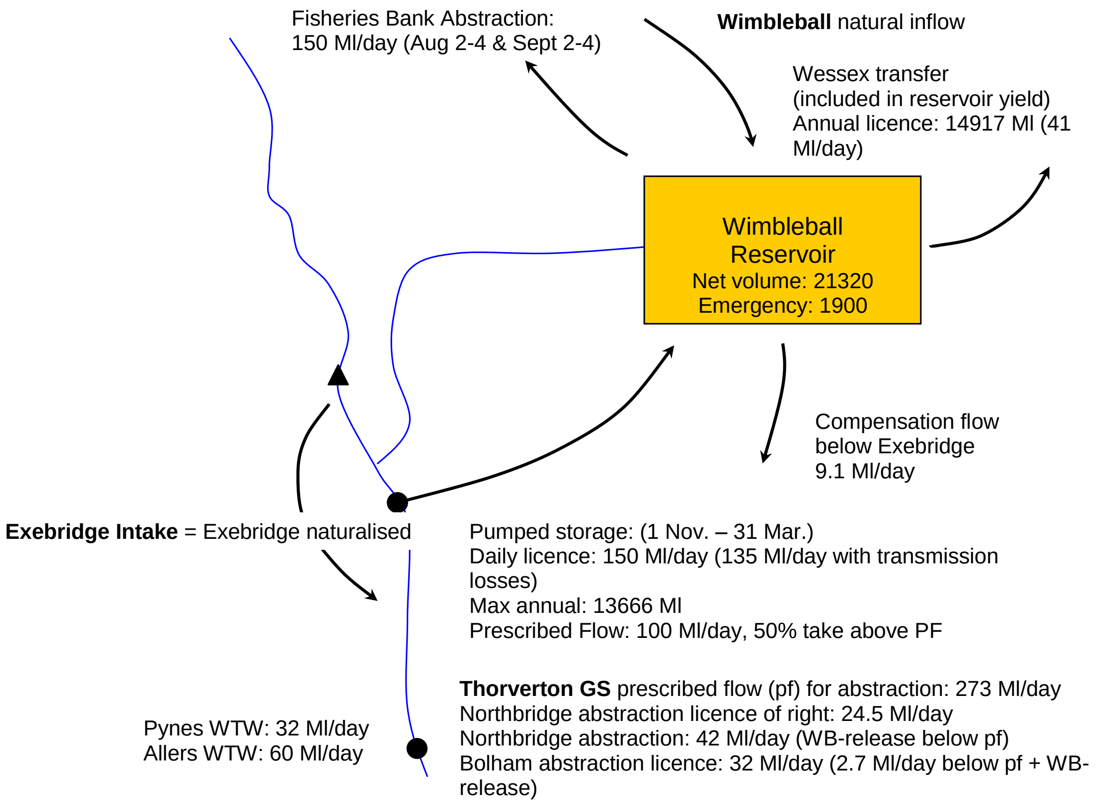


Figure 3.6 Schematic of Wimbleball water resources system

3.3 Data and model limitations

A number of data and model limitations were identified during the development of the water resources models. These are discussed below:

- **Using a monthly time step.** The use of a monthly time step in the models was necessary to make the models practical for use in a one-day interactive workshop. However this causes a degree of smoothing of the results and also required a somewhat simplified representation of the systems. The use of monthly data is mostly of importance for Wimbleball reservoir, which has a number of complex licences including fish abstraction taking place over the course of a few days in August and September. The monthly time step means that these minor features are not presented adequately in the model.

- **Modelling approach used for reconstructed flows.** It is important to be aware of the uncertainties related to the modelling approach which were highlighted in the previous 'severe' droughts study. Monthly rainfall data were collated from the Met Office from very old paper records and evaporation was based on long-term average monthly evapotranspiration for the 20th century.

- **Time period for reconstructed flows.** Reconstructed flows are available to 1803 for the Ouse but only to 1865 for the Exe. In the initial phases of the project, the team considered whether the earlier drought could be reconstructed in any reliable way for the Exe. However, the reconstruction would require further collation of rainfall data from the Met Office and rainfall–runoff modelling which was assessed to be beyond the scope and timeframe of the study.

- **Quality of hydrological data.** The climate and hydrological data may not be very reliable for the droughts from the early part of the 19th century. Available climate and hydrological data are discussed in Appendix F. In addition, limited supporting hydrological data (e.g. groundwater levels and spring flows) and anecdotal evidence of environmental impacts of rivers and aquifers are available for UK catchments for this period. However, environmental impacts can be assessed based on more recent droughts with similar characteristics.

- **Setting target demands.** The simplicity of the models and the consideration of only the part of water resource zones normally used for water resources and drought planning by the water companies made it difficult to establish realistic target demands for the models during droughts. Target demands have been set slightly higher than the deployable outputs estimated from more recent historic design droughts to balance out the smoothing taking place using a monthly time step and taking account of increased demands during droughts. For Grafham, the target demand was set to the DO with restrictions taken from Anglian Water's drought plan.

- **Supply from groundwater sources.** The effects of drought on groundwater sources have not been considered explicitly in the models, although groundwater sources have been included in the interactive models as drought measures to provide additional supply such as the resurrection of disused observation boreholes. The impacts of drought on groundwater source yields can, to some extent, be considered in a qualitative manner using the models in conjunction with available groundwater hydrographs (where available) and general assessments based on rainfall and temperatures.

Despite the limitations, the available data and simple spreadsheet models were assessed to be sufficiently accurate for testing the drought management framework under more severe drought conditions than previously considered in water company drought plans.

The implications of some of the limitations are considered in the methodology used for testing the system described in Section 5 and in developing recommendations for improvements to the drought framework presented in Section 6.

4 Drought definitions and identification

4.1 Definition of 'long drought'

There is no existing definition of 'long drought'. In an analysis of rainfall deficiencies, Jones et al. (1997) made a distinction between short duration (8–10 months) droughts ending in autumn, which generally have the greatest effect on more upland areas, and long duration (18 months) – typically two dry summers and an intervening dry winter – which have the greatest impact in southern England where replenishment of reservoirs and groundwater recharge in winter is critical for water resources. In these areas, however, the greatest impacts are likely to occur when two or more dry winters occur successively. The 'severe' droughts project (Cole and Marsh 2006, Wade et al. 2006) demonstrated that large lowland reservoirs were particularly vulnerable to long multi-season droughts.

Previous work undertaken to catalogue major historical drought episodes in England and Wales (Cole and Marsh 2006, Marsh et al. 2007b) noted that:

- the droughts with the greatest impact on water resources were generally multi-year events;
- there is a repeated tendency in historical records for dry years to cluster together, resulting in multi-year droughts which often contain shorter and more intense periods of deficiency.

Some of the most protracted clusters of this type occurred before the start of most instrumental river flow records (e.g. in the 1890–1910 period). This places a premium on adopting a long historical perspective when addressing the occurrence of long droughts.

As there is no standard definition, a working definition was adopted for this study. A long drought should last two or more years, and generally will result from a run of dry winters (similar to the situation in 2004–2006). However, some flexibility is required owing to the range of different metrics which can be used to quantify drought severity and duration (see Section 4.2) and the contrasting vulnerability to multi-year droughts in different parts of the country. It is also assumed that the long droughts are likely to be spatially extensive, and associated with well-documented major societal and environmental impacts.

4.2 Overview of drought metrics

Droughts are multifaceted both in their meteorological character and range of impacts. While in broad terms the concept of drought is readily recognised by the public at large, translating this intuitive understanding into an objective procedure for indexing or assessing drought severity is far from straightforward. In part this reflects the difficulties of quantifying a phenomenon which varies in its areal extent, duration and intensity both regionally and locally.

Any comprehensive attempt to identify drought episodes and to index drought severity needs to address the different, if overlapping, impacts associated with meteorological droughts, hydrological droughts and agricultural droughts (see Section 1.3). In addition, contrasting hydrogeological characteristics, water resources management options and patterns of water usage can make for substantially different vulnerabilities within any given region.

An extensive range of existing drought indicators is available; see Hisdal et al. (2004) for a review of some of the widely used techniques. No single methodology for assessing drought severity is likely to reflect the full range of drought impacts and the choice of methodology used to characterise droughts will depend on:

- the research objective in question;
- the availability and quality of data;
- the geographical region where the analysis is being applied.

For this study, a range of widely used drought metrics was employed to facilitate the identification of long droughts. Appendix C provides details of the various methods used along with a brief summary of their suitability for identifying and characterising multi-year drought events in England and Wales. Section 4.5 further considers the practical utility of these methods for drought management in general.

As both case study catchments (see Section 3) have very long runoff records, the majority of metrics were selected for their suitability for using river flow data – though most of the indicators can also be applied to other data types. Some metrics based primarily on meteorological data were considered and are also discussed in Appendix C.

4.3 Characterisation and identification of long droughts

The drought metrics described in Section 4.2 and Appendix C are applied in this section to long reconstructed flow records for the Ely Ouse and the Exe, as well as to complementary rainfall and groundwater records.

A brief description of the long reconstructed records and their utility and limitations is given in Appendix C. The records are highly indicative of historical flow variability, but it is important to bear in mind that they are model outputs and are subject to a range of uncertainties (discussed in detail in Appendix C).

The aim is to:

- identify those droughts that can be considered ‘long’ droughts;
- explore mechanisms for characterising their severity and duration using available indicators.

4.3.1 Runoff deficiencies

Previous work (Jones et al. 2003, Cole and Marsh 2006) examined *n*-month runoff deficiencies in reconstructed flow records. Cole and Marsh (2006) focused on accumulated runoff over periods of 6, 12 and 18 months. To complement this previous work, the present study calculated and ranked longer-term deficiencies. Tables 4.1 and 4.2 show the ranked 36- and 60-month runoff deficiencies, respectively, for the two study catchments.

Table 4.1 Maximum 36- and 60-month runoff deficiencies for the Ely Ouse (synthetic naturalised series from 1801–2002) [1]

36-month deficiencies				60-month deficiencies			
Rank	**Runoff (mm)**	**% of LTA [2]**	**End date**	**Rank**	**Runoff (mm)**	**% of LTA**	**End date**
1	232.72	49.41	**Jun 1816**	1	430.50	54.89	**Dec 1806**
2	242.12	51.33	**Dec 1804**	2	493.47	62.96	**Feb 1903**
3	258.48	54.88	**Aug 1808**	3	496.58	63.46	**Nov 1817**
4	261.89	55.58	**Apr 1903**	4	503.13	64.26	**Jun 1859**
5	270.08	57.35	Sep 1923	5	530.65	67.79	Aug 1946
6	270.15	57.38	Nov 1935	6	572.05	72.99	**Feb 1839**
7	271.08	57.55	**Jul 1865**	7	571.83	73.03	**Jun 1909**
8	272.83	57.87	**Feb 1896**	8	572.99	73.06	**Dec 1865**
9	278.55	59.14	Aug 1974				
10	280.25	59.45	Feb 1946				

Notes [1] Deficiencies before 1910 are in bold.

[2] Long-term average

Table 4.2 Maximum 36- and 60-month runoff deficiencies for the Exe (synthetic naturalised series from 1865 – 2002) [1]

36-month deficiencies				60-month deficiencies			
Rank	**Runoff (mm)**	**% of LTA [2]**	**End Date**	**Rank**	**Runoff (mm)**	**% of LTA**	**End date**
1	1649.95	68.96	**Dec 1889**	1	2881.93	73.16	**Jun 1891**
2	1681.42	70.52	**Mar 1907**	2	2916.93	73.90	**Feb 1909**
3	1798.79	75.52	May 1965	3	3324.33	84.43	Aug 1976
4	1817.45	76.49	Nov 1934	4	3432.92	87.23	**Sep 1902**
5	1918.80	80.55	May 1944	5	3474.04	87.92	Jan 1966
6	1918.67	80.57	Jun 1950	6	3480.40	88.25	Mar 1993
7	1942.09	81.28	Jan 1974	7	3492.26	88.64	**May 1872**
8	1949.84	81.49	**Dec 1871**	8			
9	1979.78	82.96	**Feb 1903**	9			
10	2001.85	83.66	**Dec 1898**	10			

Notes [1] Deficiencies before 1910 are in bold.

[2] Long-term average

A notable feature of the results, which agree with those from the shorter periods used in previous work, is the prevalence of events from the 19th century and early 20th century – particularly in the case of the Ely Ouse.

Ely Ouse

Over both the three- and five-year timescale, the four greatest deficiencies for the Ely Ouse are from before 1910. Particularly notable are:

- the two 36-month deficiencies in the 1802–1808 period;
- a sustained period of suppressed runoff;
- the two 36-month deficiencies in the 1893–1903 period.

These periods also occur within the 60-month accumulations, with the five years leading to 1909 also featuring prominently. The occurrence of notable five-year deficiencies from 1854–1859 and 1860–1865 suggests these periods also warrant attention as a period of persistent deficiency.

The high rankings of the 1812–1817 period – not considered a major drought by Cole and Marsh (2006) due to lack of evidence of impacts – suggest this period also warrants inclusion as a notable long drought for the Ely Ouse catchment.

The major deficiencies of the 20th century agree with those identified over 18-month durations by Cole and Marsh (2006), but tend to rank lower in the present analysis, i.e. the prevalence of pre-1910 events relative to post-1910 events is even more marked when long deficiencies are studied.

Exe

While the relative ranking of the deficiencies is different in the Exe series, most of the episodes identified correspond to similar major droughts – again principally in agreement with the major droughts for England and Wales droughts in Table 1 of Cole and Marsh (2006).

Compared with the Ely Ouse, there are fewer deficiencies from before 1910, with higher rankings thus attributed to the major 20th century droughts such as 1962–1965 and 1931–1934. This is partly due to the shorter record considered in the analysis.

Influence of winter season

The extent to which the winter season is influential in dictating runoff deficiencies is illustrated in Figure 4.1. In general, depressed runoff in the winter season was much more common in the 1800s (as shown for rainfall by various authors, e.g. Jones and Conway 1997, Marsh et al. 2007b) compared with the 1900s. Protracted periods of winters with depressed runoff are evident including from 1800–1820 and 1855–1870, and over the 1885–1910 period. With regard to the early part of the series, 1800–1810 falls within the ‘Little Ice Age’ and so may be considered part of a different climatic regime.

These runs of below average winters are clearly a major driver of long droughts; little work has been done to explore the causes for this ‘clustering’ of dry winters in the historical record.

Abnormal synoptic conditions, associated with persistent anticyclonic conditions and the associated deflection of frontal rainfall, are known to be important in recent longer droughts (1975–1976, 1995–1997, 1988–1992).

The climatological conditions associated with such persistence (e.g. in terms of large scale modes of variability such as the North Atlantic Oscillation) have been examined for some drought events, but have yet to be fully elucidated over a long timescale.

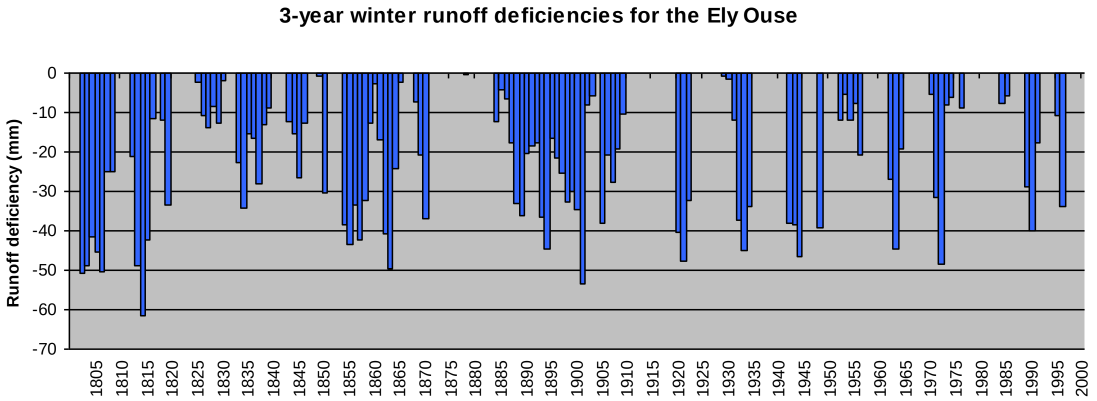


Figure 4.1 Runoff deficiencies for the November to April period for the Ely Ouse, averaged over three successive winters

4.3.2 Drought Severity Index

The Drought Severity Index (DSI) (after Bryant et al. 1994) emphasises a crucial difference between the sites in terms of the duration of major droughts (Figure 4.2). Droughts in the Exe tend to be of a different character, of shorter duration. Deficiencies build up rapidly, but then tend to be terminated quickly; there are a higher number of shorter, intense periods of deficiency. This is a function of the greater month-to-month variability in flow which is itself related to the higher short-term variability of rainfall in western England and the fact that the Exe is a steeper, more responsive catchment with less natural storage. The Ely Ouse catchment is subject to more protracted runoff deficiencies of three or more years, as would be expected given the higher groundwater storage contribution to flows on the Ely Ouse.[7]

On the Exe, the longest droughts generally cover a two-year period of deficiency. The major droughts correspond with those identified using the *n*-month deficiencies, although as the droughts identified by the DSI are shorter than the *n*-month periods used, there are inevitable differences; for example, the 1976 drought has one of the highest deficiencies using the DSI approach.

Figure 4.3 shows DSI extending back to 1803 for the Ely Ouse and demonstrates that the method identifies the main runoff droughts selected using the *n*-month deficiencies, although the termination criteria are clearly influential; 1802–1810 becomes one long drought on the Ely Ouse rather than being identified as separate periods using the *n*-day approach. The relative magnitude of the various drought events (while broadly comparable) is different to those derived using *n*-day deficiencies.

A feature of the deficiencies in the Ouse record is the close sequencing of some long droughts – particularly notable across the turn of the 20th century when several droughts of three years (or more) are separated by relatively short periods. The clustering of droughts in this period, while shorter, is also very notable on the Exe (Figure 4.2). For most of these events, the periods of deficiency are separated only by very short periods of above average flow and discriminating them as individual droughts is likely to be highly dependent on the termination criteria.

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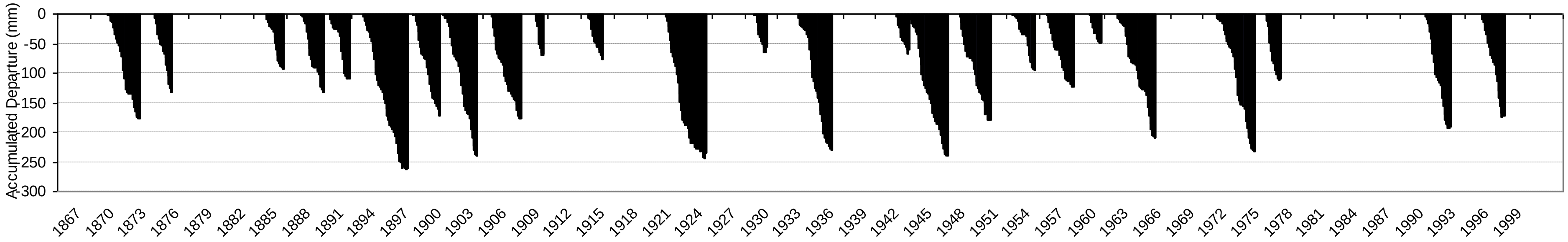
[7] BFIHOST for the Ely Ouse is 0.74 (Marsh and Hannaford 2008). BFIHOST is a measure of permeability estimated from soil properties and, in the case of this catchment, is more representative than the Base Flow Index (BFI) (0.46). The BFI for Ely Ouse is derived from the flow record, which is heavily influenced by complex water transfers and the hydrometric setup of the Denver gauging station.

One of the benefits of this approach is that it can be applied to precipitation and groundwater series. Figure 4.3 illustrates the DSI time series for a long rainfall record from Cambridge located within the Ely Ouse catchment. The Cambridge rainfall series demonstrates that DSI does not pick up longer drought periods. The highest accumulated rainfall deficits correspond to droughts identified using runoff, but the longer droughts do not show using rainfall data because the termination criteria are reached more frequently in the rainfall records (given the higher variability of rainfall, particularly where runoff is ‘buffered’ by storage). Some lack of congruence between rainfall and river flow records is to be expected given the importance of evaporative demands in generating the flow deficiencies.

Figure 4.3 also shows DSI applied to the Therfield Rectory groundwater record. This borehole, in the Chalk of Hertfordshire, is one of the longest groundwater records in the National Hydrological Monitoring programme database. The site is located in the headwaters in the far south of the Ely Ouse catchment. The termination criteria are not applied to the groundwater record (i.e. the plot shows a rolling cumulative average for both positive and negative deficiencies) following the recommendation by Bryant et al. (1994).

In general, the extended periods of groundwater deficiency correspond to the long droughts identified using runoff records. The impacts of long dry spells on groundwater levels are clear; in the record up to 1914, levels were consistently below average and protracted deficiencies are in evidence through the record (e.g. in the early 1920s, throughout the 1940s). The more recent droughts of the 1990s show as more prominent when the groundwater data are used, which may partly reflect increased abstractions in the recent past. This analysis underlines the extent to which groundwater resources are vulnerable to long periods of below-average winter rainfall (see Section 4.4).

Ely Ouse at Denver sluice



Exe at Thorverton

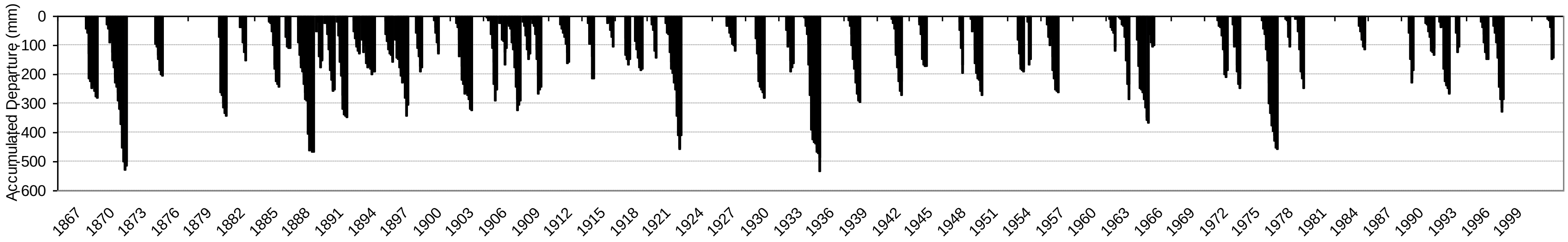
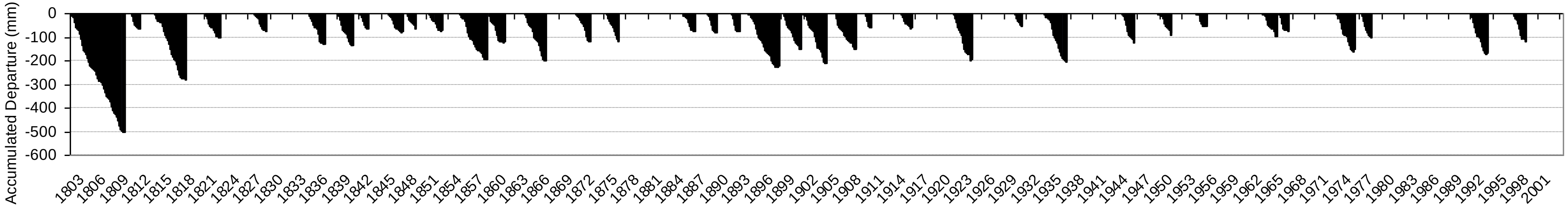
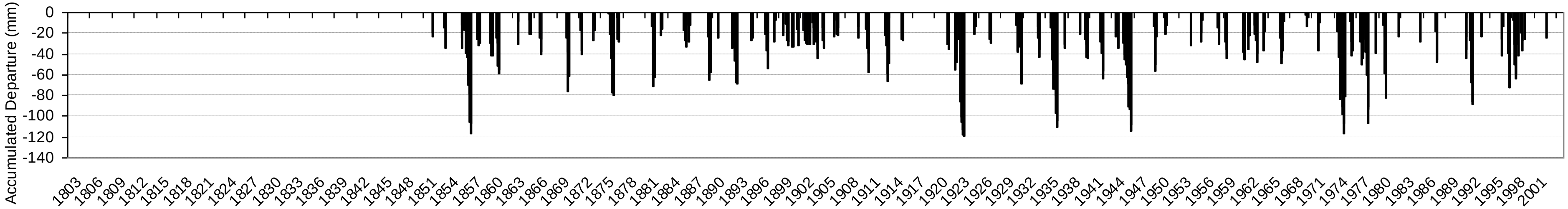


Figure 4.2 Drought Severity Index based on accumulated monthly departures from the monthly mean for the Ely Ouse and Exe reconstructed records (1865–2002)

Ely Ouse reconstructed series, 1801–2002



Cambridge long rainfall record



Therfield Rectory groundwater record

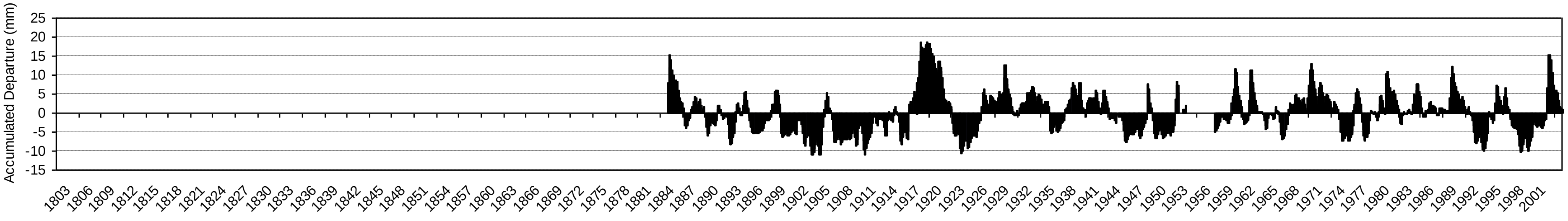


Figure 4.3 Comparison of Drought Severity Index for runoff, rainfall and groundwater records in the Ely Ouse catchment

4.3.3 Threshold method and sequent peak algorithm

Tables 4.3 and 4.4 show the top 10 droughts on the basis of the volume below the Q70[8] threshold for the Ely Ouse and Exe respectively. In general, similar events are identified as when DSI is used. The advantage of this approach is that it allows drought 'events' to be objectively defined in relation to a flow threshold, and as such the duration of the event can be quantified – albeit against an arbitrary threshold (the duration would be different if, for example, Q90[9] was used).

For the Ely Ouse, only the top two events extend over more than two years. However, five droughts had 18-months below the monthly varying Q70 threshold; four of these were before 1910. On the Exe, most of the events are of shorter duration – generally within-year deficiencies. The higher flow variability in this catchment means that long-duration deficiencies do not develop.

Table 4.3 Ten longest drought deficits below the Q70 flow threshold for the Ely Ouse

	Start	End	Duration (months)	Deficit volume (m^3/s)
1	Dec 1813	Jun 1816	31	107.32
2	Jan 1802	Dec 1803	24	106.80
3	May 1901	Feb 1903	22	60.25
4	Aug 1933	Mar 1935	20	84.64
5	Apr 1893	Oct 1894	19	47.77
6	Jul 1943	Sep 1944	15	56.52
7	Mar 1874	May 1875	15	33.69
8	Feb 1921	Mar 1922	14	84.08
9	Apr 1996	May 1997	14	59.00
10	Jun 1990	Jun 1991	13	54.13

Table 4.4 Ten longest drought deficits below the Q70 flow threshold for the Exe

	Start	End	Duration (months)	Deficit volume (m^3/s)
1	Feb 1921	Dec 1921	11	36.84
2	Aug 1933	Mar 1934	8	41.31
3	Feb 1887	Sep 1887	8	18.45
4	Jun 1937	Dec 1937	7	11.45
5	Apr 1870	Sep 1870	6	14.41
6	May 1919	Oct 1919	6	8.88
7	Jan 1929	May 1929	5	23.64
8	Oct 1904	Feb 1905	5	23.31
9	Dec 1890	Apr 1891	5	23.26
10	Feb 1956	Jun 1956	5	17.05

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[8] Q70 is defined as the flow exceeded for 70 per cent of the time.

[9] Q90 is defined as the flow exceeded for 90 per cent of the time.

Table 4.5 shows the top 10 drought events ranked by duration (the principal aim is to examine long droughts) identified by the sequent peak algorithm (SPA) for the Ely Ouse using Q70 as a threshold. Results from the Exe are not shown as the SPA also only identifies short, within-year deficits.

The analysis yields qualitatively similar results in terms of the main long droughts to the *n*-day minimum and DSI approaches. Most of the droughts identified are the same as those identified using the threshold method, although differences in the start and end dates and relative rankings demonstrate the sensitivity of these methods to the particular ways in which droughts are defined.

Table 4.5 Ten longest droughts according to SPA analysis for the Ely Ouse at Denver sluice

Rank	Date	Duration (months)	Volume (m^3/s)
1	Nov 1803	20	59.72
2	Nov 1815	19	36.87
3	Dec 1991	19	36.22
4	Nov 1934	18	45.78
5	Oct 1997	18	29.12
6	Oct 1894	18	25.55
7	Nov 1973	18	24.38
8	Nov 1902	18	22.82
9	Oct 1944	17	32.82
10	Sep 1855	16	23.82

4.3.4 Other indicators

The SPI12 (i.e. SPI averaged over a 12-month period) is shown in Figure 4.4 for two regions relevant to the study catchments – South East UK (SE UK) and South West UK (SW UK) in Figure 4.4. The advantage of using SPI12 is that the variability in rainfall is smoothed and periods of persistent above- and below-average precipitation become readily apparent.

The SPI12 time series confirm that the major long meteorological droughts (in terms of periods with negative SPI) agree with the hydrological droughts of the 20th century identified using the reconstructed records, e.g. pre-1910, 1940–1945, 1963–1966, the early 1990s. The plots demonstrate neatly the difference between duration and magnitude of some events; for example, 1971–1974 appears as a longer duration, lower magnitude event, whereas 1976 is of shorter duration but attains one of the highest SPI deficiencies in both records. The 2004–2006 drought appears as a relatively minor deficiency compared with historical droughts.

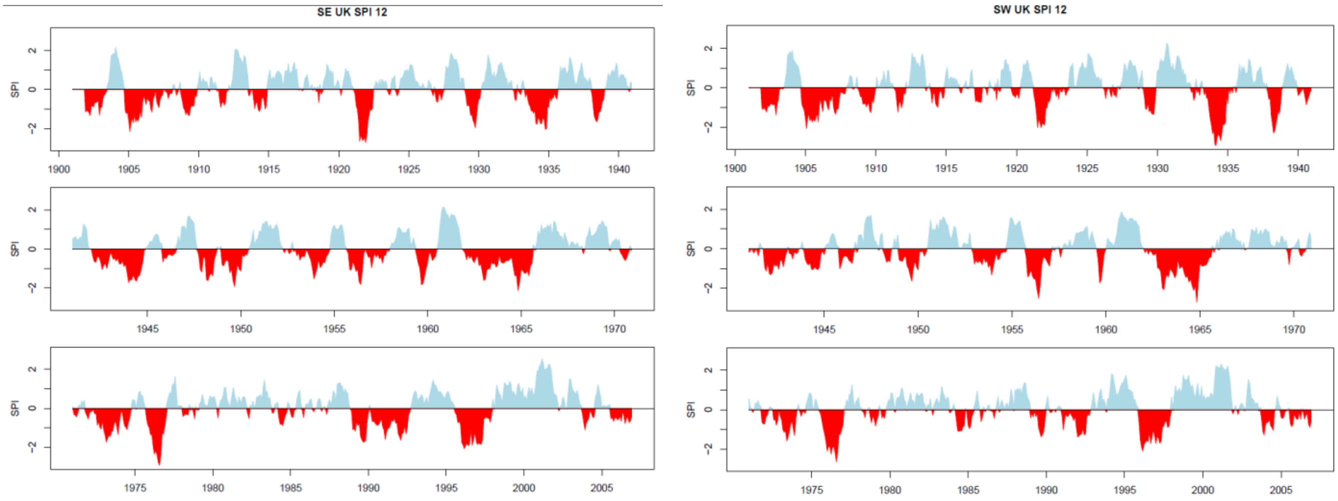


Figure 4.4 Time series of SPI 12 for south-west and south-east England

The regionalised version of the SPI (RSPI) and the Regional Drought Index (RDI) for South East England are shown in Figure 4.5 – an output from the drought catalogue produced by the spatial coherence project (Report SC070079/R1; Lloyd Hughes et al. 2010).

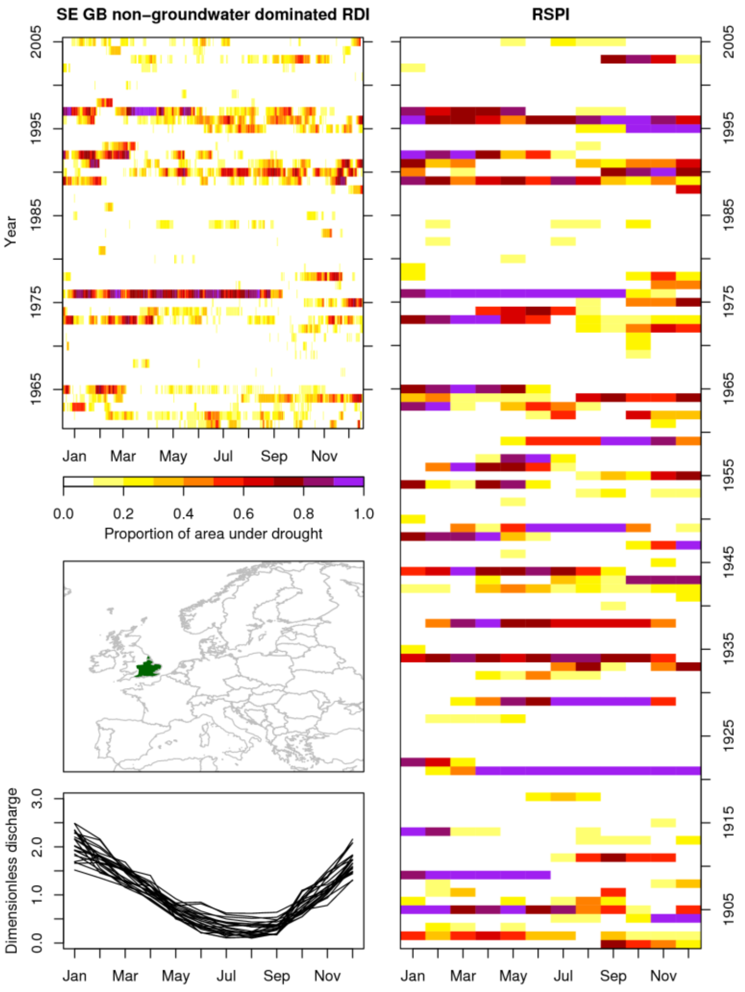


Figure 4.5 Example of a drought catalogue page for South East Great Britain (Lloyd Hughes et al. 2010)

These indicators demonstrate that many of the long drought periods identified using the individual catchment records are regionally significant events affecting a large proportion of south-east England.

Furthermore, deficiencies occur throughout the year and major winter deficits can be observed during long drought episodes. In the droughts of the 1990s, there are long periods when 90 per cent of the region was in a meteorological drought for several months; similarly, 60 per cent or more catchments were under drought (below a daily-varying Q90) for long periods, e.g. late 1995 to early 1996, or during the spring of 1997 when more than 90 per cent of catchments were under drought. 1975–1976 shows as a very spatially coherent drought over a long period. For other historical droughts, there are long periods of spatially coherent meteorological drought, such 1921–22 when over 90 per cent of the region was under drought for over nine months.

4.4 Environmental impacts of historical droughts

The importance of water in every aspect of life dictates that droughts will have a significant impact across many social, economic and environmental settings. Media reporting of drought events tends to focus on the subsequent effects on societal welfare and the economy.

The ‘severe’ droughts study considered the impact of historical droughts but focused primarily on impacts on water resources (see Cole and Marsh 2006, Marsh et al. 2007b).

Considerably less attention has been given to environmental impacts, which can be just as severe in their own right. This section summarises some of these impacts, citing examples from historical droughts in the UK. The focus is on long multi-year droughts, although in such droughts the most serious impacts often arise from intense ‘summer’ drought phases, e.g. in the extremely hot and dry summer of 1995 which was part of the longer 1995–1997 drought.

The focus of this brief review is on impacts related to hydrological drought rather than meteorological or agricultural droughts. It covers water quality, groundwater and drainage networks, and hydro-ecological impacts.

4.4.1 Water quality impacts

The influence of sewage treatment works on the low flow hydrology of channels can mean that almost all flow is sewage effluent at the height of a drought, which can often result in deleterious consequences for water quality. Changes in the chemical composition of river water during droughts tends to be exhibited through increasing concentrations of solutes including K, Mg, Na, Ca, Cl and NO_3 ions, with concurrent impacts on aquatic biodiversity and water quality.

Water temperatures are an often-overlooked facet of water quality, yet are important to consider because they affect the rate of reactions and the dissolved oxygen capacity of water. They also control the suitability of water to be inhabited by a subset of species.

During droughts, increased air temperatures (augmented by the warming effect of a higher proportion of sewage effluent at low flows) can result in a substantial increase in river temperatures; Doornkamp et al. (1980) reported that the River Exe at Thorverton was 6°C warmer in June 1976 than in June 1977.

Water quality impacts have been reported from recent droughts, most notably 1976; for example, saline incursions occurred due to low river flows and algal blooms were widespread (Davies 1978). There are some isolated examples of documentary evidence suggesting impacts of historical droughts; for example, when the Exe was reported as 'little better than a sewer' during the 1874 drought (BHS 2009).

Biological factors can have a heavy impact on many aspects of water quality. The excess nutrient load in waterways in mid-Bedfordshire in 1976 triggered extensive growth of bacteria and fungi, which in turn reduced the dissolved oxygen content (DOC) of the river water at the height of the drought. This same expansion of waterborne micro-organisms was further aided by elevated water temperatures of 16–18°C (Doornkamp et al. 1980).

4.4.2 Groundwater and drainage network impacts

Groundwater levels are especially vulnerable to deficit conditions following dry winters, the season typically associated with replenishment of aquifers. This is particularly so for periods of successive winters with rainfall deficiencies; the most extreme expression of the 1988–1992 long drought was in the groundwater-dominated eastern lowlands of the UK, a consequence of frequently insignificant aquifer recharge throughout this period. The four-year effective rainfall minima reached over 1988–1992 was unprecedented in the 20th century (Marsh et al. 1994).

Geological setting can play an important role in determining the extent of network shrinkage. Groundwater-dominated stream networks become vulnerable to reductions in extent in the case of multiple consecutive dry winters. Shrinkage of the drainage network in lowland groundwater catchments was reported widely during the 2004–2006 drought, although there are reports of down-valley recession during historical long droughts, e.g. in 1921 when the Kennet retreated 16 miles downstream (BHS 2009).

Dry wells and springs feature prominently as recorded impacts in the range of anecdotal evidence of the long drought periods from 1890–1910 brought together by Cole and Marsh (2006). The Wendover Springs, a rare example of a springflow record with data from the turn of the 20th century, was reported to have dried up repeatedly during this period (Bayliss et al. 2004).

River levels in catchments with lower storage potential (impermeable geology) are more vulnerable to reduction in the extent of the drainage network during average drought events and dry summers (Zaidman et al. 2002). Minor streams in isolated sections dry up before they reach the main arteries. A mid-August 1976 survey of the River Soar in Leicestershire measured a drainage net that was 39 per cent of its original 1,094 km length (Doornkamp et al. 1980).

Human impact can also have an effect on the susceptibility of drainage networks to shrinkage. Where reservoir releases or water transfers supplement natural flows (predominantly in more developed and populated areas), streams are less likely to dry up entirely. For example, on the River Soar in Leicestershire during the 1976 drought, 75 per cent of right bank tributaries had run dry but only 44 per cent of left bank channels dried up. The perseverance of the latter had much to do with supplementary groundwater pumped from local coal mines and the regulation of flow by reservoirs, factors which did not impact upon the more natural and agriculturally influenced right bank streams (Doornkamp et al. 1980).

Where catchments are pumped from groundwater storage, any natural shrinkage is exacerbated further as springs with increasingly low head fail successively. This effect is a particularly important factor in more recent and/or more severe droughts such as that of 1988–1992; during this drought, over-abstraction contributed to the extreme low flows and network contraction seen in many chalk catchments and was partly responsible for the introduction of ‘alleviation of low flow’ (ALF) schemes (Clayton et al. 2008).

4.4.3 Hydro-ecological impacts

Prolonged or severe drought conditions can trigger changes in the microbiological composition of stream water. The impact of low river levels is exacerbated by low oxygen levels and increasing concentrations of pollutants, which can have deleterious effects on ecosystems. For example, aided by increasing proportions of sewage effluent, a single species and polluted drought biota emerged in mid-Bedfordshire waterways in 1976 (Doornkamp et al. 1980).

Long droughts are likely to have a particularly major impact on ecosystems owing to the effect of prolonged low river levels and related network contraction. During the 1988–1992 drought, a vast reduction in the extent of the drainage network was responsible for significant losses of aquatic life (Marsh et al. 1994). Reduced inputs through the stream network and intense evaporation during 2004–2006 led to drying up of rivers and ponds; fish rescues were necessary in isolated and declining stretches of river (Marsh et al. 2007b).

The lack of spates and drying up of headwater tributaries represents a particular risk to migratory fish that require sufficient flow to trigger upstream movement and to reach their spawning grounds. Flow in the river interacts with channel morphology to create the patterns of depth, velocity and width that freshwater communities utilise. Prolonged periods of low flow can have adverse affects on river health through a lack of dilution and by altering the physical conditions in the river. During periods of low flow, less wetted area may be available, depths may be shallower and velocities slower. This can be a particular problem for young salmonid fish, which prefer moderate velocities and avoid very shallow water while drift-feeding.

Only a limited amount of work has been carried out to quantify the habitat loss that occurs during droughts. Figure 4.6 provides a comparison of habitat availability for drift-feeding juvenile trout during two drought events. Low flows in the summer of 2006 on the River Kennet had an impact on habitat availability compared with the more typical conditions for 2004. In 1976, however (when flows were the lowest in a 45 year record), the habitat availability was much reduced. In the latter case, the combination of a very dry winter combined with an extremely dry summer and associated heatwave served to exacerbate the impacts of the drought.

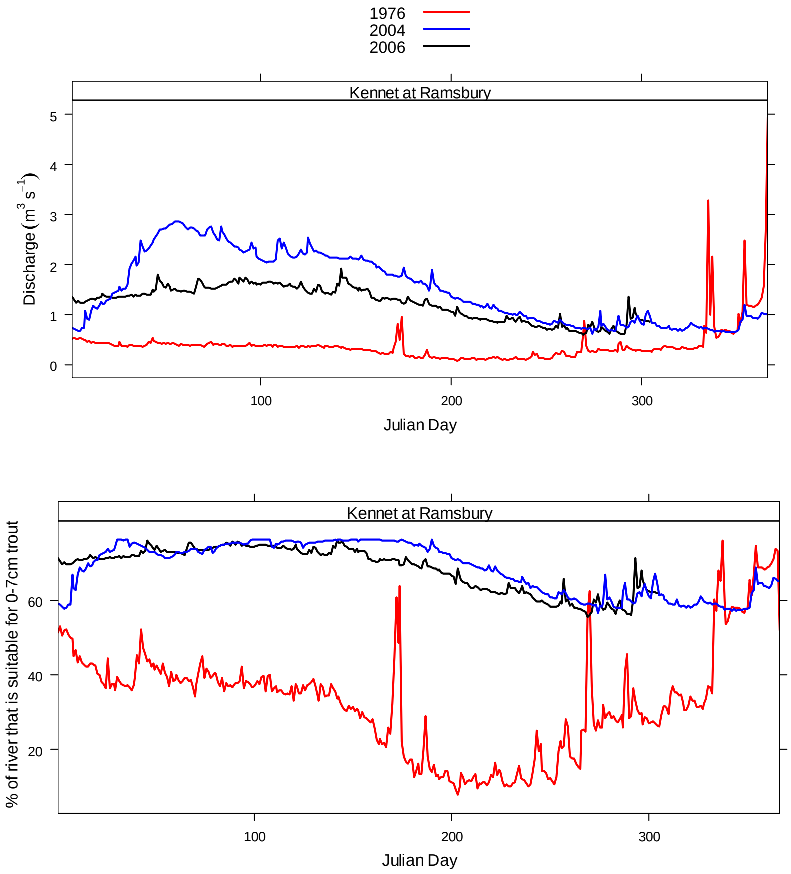


Figure 4.6 Comparison of habitat availability in 2004 and 2006, and 1976, on the River Kennet (from Marsh et al. 2007b)

Generally, there is a relatively limited amount of information available on hydro-ecological impacts of major droughts. Ecological considerations have only really been raised to the fore during the relatively recent past; even during the 1975–1976 drought, there are comparatively few reports of ecological impacts compared with the vast range of material assembled on agricultural and other socio-economic impacts (e.g. Doornkamp et al.1980). Reports produced in the wake of the droughts of the 1990s contain passing references (for example to 20,000 fish being killed in the River Trent in 1995; Cole and Marsh 2006), while Marsh et al. (2007b) provide some background information on ecological impacts of the 2004–2006 drought.

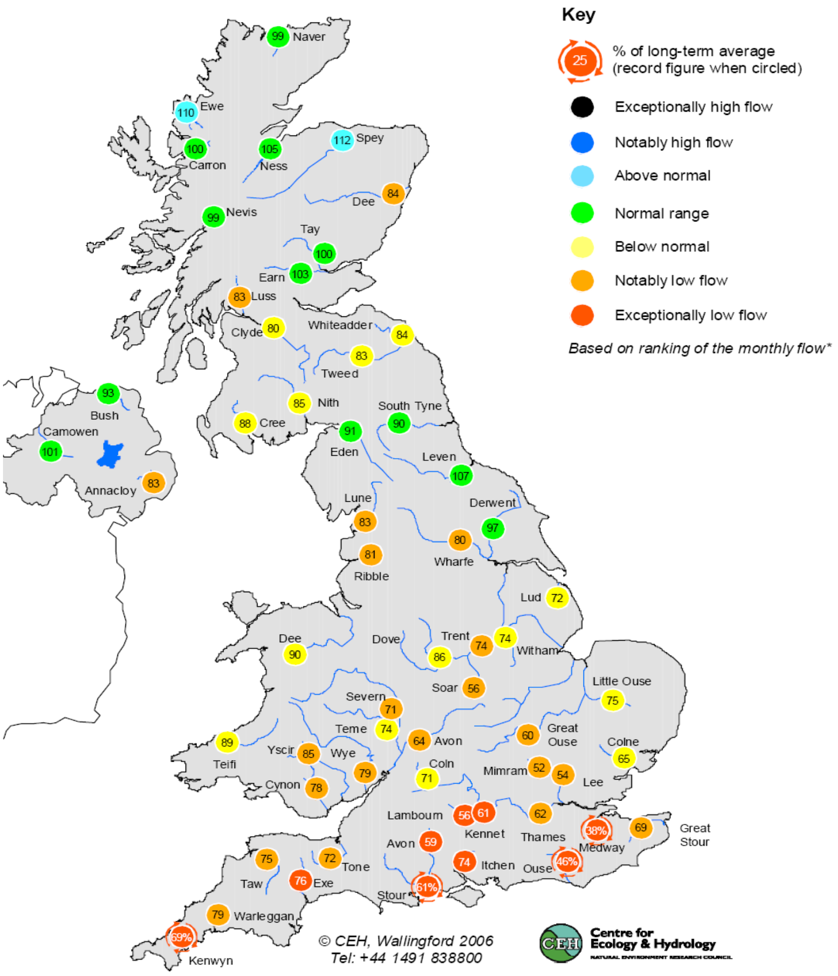
In particular, very few sources provide information on the environmental consequences of multi-year droughts, particularly in groundwater catchments. This remains an important avenue for monitoring in future drought events.

4.5 Practical uses of drought indicators

The indicators used in this study represent a powerful set of tools for characterising major droughts. However, the various indicators are not equally suitable for different applications. This summary discusses briefly the suitability of the indicators for practical use in drought management.

Simple runoff deficiencies provide a convenient way of ranking periods of a given duration (e.g. 18-month, 36-month used in this report). The method is very easy to implement, but is based on a fixed duration period, so only gives the relative ranking of major deficiency periods rather than extracting discrete drought events from a hydrological record. However, the method is well suited to placing contemporary drought deficiencies in the context of previous deficiencies of a similar duration. In Tables 4.1 and 4.2, for example, the runoff deficiencies in contemporary long droughts can compared to 19th century events.

Similar mechanisms can be used in an operational capacity to compare runoff or rainfall deficiencies with historical periods. Deficiencies expressed relative to a long-term average are widely used in drought monitoring, e.g. in the Hydrological Summaries produced by the National Hydrological Monitoring Programme (CEH 2009) and the Environment Agency's Water Situation Reports. Figure 4.7 shows runoff deficiencies during the 2004–2006 drought based on an accumulation from November 2004 to August 2006. For each of these catchments, the runoff over this period is compared with all previous 22-month November–April deficiencies. These can then be ranked and a colour coding scheme applied to compare contemporary conditions with the historical record – in this case highlighting the exceptionally low runoff seen in southern England.



*Comparisons based on percentage flows alone can be misleading. A given percentage flow can represent extreme drought conditions in permeable catchments where flows patterns are relatively stable but well within the normal range in impermeable catchments where the natural variation in flows is much greater. Note: the period of record on which these percentages are based varies from station to station.

Figure 4.7 November 2004–August 2006 runoff accumulations as a percentage of the long term average

Source: Water Watch (http://www.ceh.ac.uk/data/nrfa/water_watch.html)

The Drought Severity Index (DSI) is potentially a powerful tool for characterising droughts as it allows the timing and intensity of events to be established. The study has shown this method to be suitable for examining long droughts, as runoff or rainfall deficiencies can develop over a period of seasons or years. However, it is highly sensitive to the termination criteria applied. Provided a consistent rule is applied (e.g. using the three-month rule), droughts in a hydrological time series can be discriminated and compared. From a drought monitoring perspective, the index could usefully be applied to monitor developing drought conditions in a single catchment or region by comparing the current month DSI with DSI values in historical droughts. However, it is vital that the termination rule is hydrologically meaningful; three months of below-average rainfall may be crucial to a reservoir in one part of the country but completely unsuitable for establishing the resilience of a groundwater supply system in another region. This limits the utility of the DSI to comparisons between catchments or regions.

If the method is to be used widely, further work is required to identify the most appropriate critical periods for water resources provision in different regions and water supply systems. Future research should be directed at developing a more sophisticated version of DSI, which employs termination criteria relevant to particular systems; for example, a version that gives higher weighting to winter rainfall deficits in groundwater areas which are dependent on winter recharge.

The threshold method and SPA are highly useful for identifying particular drought events. The threshold method is widely used in the literature as a means of identifying periods of low flow for frequency analysis or for testing for long-term change in drought characteristics (e.g. Hisdal et al. 2004, Fleig et al. 2006). A version of the threshold method (applied to daily river flow data) is used for drought identification in the European drought catalogue (Lloyd-Hughes et al. 2010).

Threshold methods provide a way of objectively identifying the start, end and intensity of drought events. The method is sensitive to the flow threshold used but, provided a consistent threshold is applied, comparisons can be made between regions. A threshold which varies throughout the year (as applied in this study) is more suitable for characterising multi-season droughts. These methodologies are probably less suited for drought monitoring as they are more complex to apply.

The threshold method and SPA are robust, defensible ways of identifying droughts, though the parameters used to characterise the events (duration and maximum deficit volume) still depend on the configuration of the methodologies. While the SPA and threshold methods do not employ such arbitrary termination criteria, as used by with the DSI approach, the drought duration calculated using these methods is still only a statistical characterisation and not necessarily a reflection of the full extent of a drought.

Figure 4.8 demonstrates that, over the ‘long drought’ period of 1890–1910, the SPA picks up two relatively long drought sequences (ending in 1894 and 1902) as well as a number of relatively short drought sequences which, using the DSI approach, are represented as continuing deficiencies (compare Figure 4.8 with Figure 4.4).

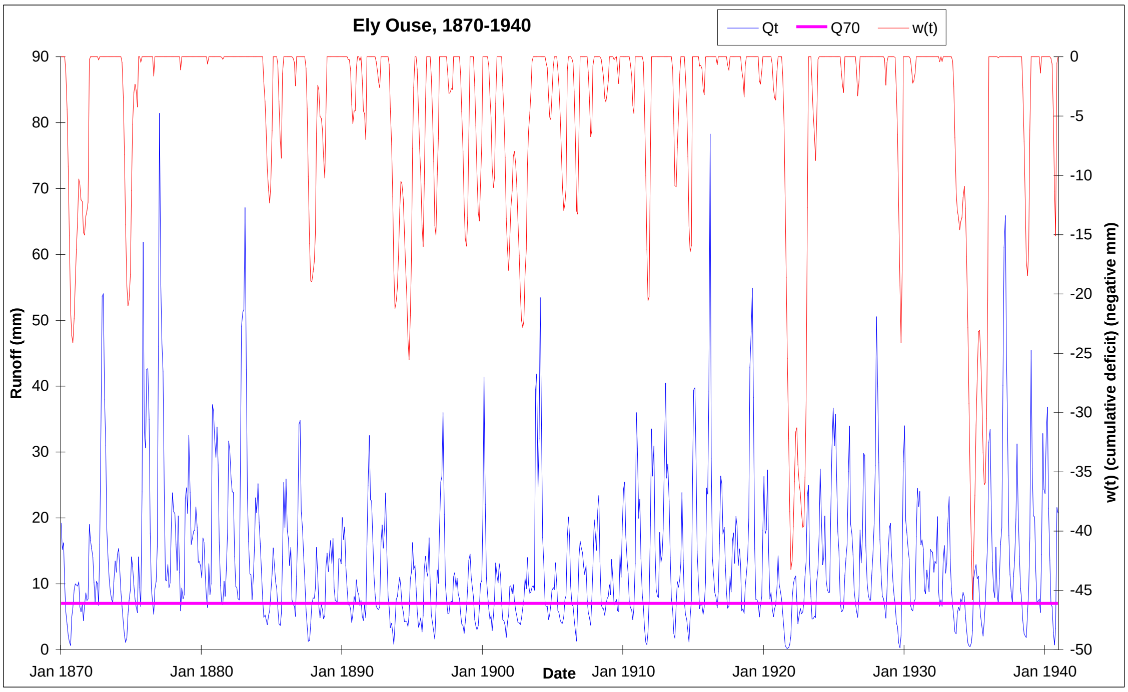


Figure 4.8 Illustration of droughts identified using the sequent peak algorithm for the 1870–1940 period

One weakness of all these hydrological drought indicators is that they provide:

- only a mechanistic view of the severity of a drought event;
- little indication of the nature of the drought in terms of impacts.

In addition, this project chose the metrics so as to deliberately focus on long droughts and this formulation may have masked some of the key differences between events in terms of their temporal evolution and seasonality. For example, a weakness of using runoff deficiencies is that the severity of the event is characterised only by an average flow for the long period; there may actually have been more severe episodes within these periods.

On the Ely Ouse, the period 1971–1974 is a notable three year deficiency (Table 4.1) and this also features as a prominent drought using DSI and SPA. However, this deficiency did not result in major societal impacts and was not considered a major drought (Cole and Marsh 2006). In contrast, 1975–76 ranks only 14th in terms of runoff deficiencies and appears to be a less important event; however, it is the benchmark drought across many parts of England and Wales. In the latter case, the combination of a dry winter with an intense hot, dry summer was the reason for the extensive impacts, but this timing is not captured by the long drought metrics.

Standardised Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI) are discussed briefly in Appendix C but were not a major part of this project, which focuses on hydrological rather than meteorological or agricultural droughts. These indicators are widely used in the literature; the SPI has been employed to develop a drought climatology for Europe (Lloyd-Hughes and Saunders 2002) and is used frequently in national- or regional-scale drought studies.

From the perspective of drought monitoring and forecasting, the advantage of the SPI is that it can be produced from readily available gridded data and has potential for application in near-real-time. SPI maps are routinely produced for the USA by the National Drought Mitigation Center and are part of the early warning monitoring undertaken by the prototype European Drought Observatory: (http://edo.jrc.ec.europa.eu/php/index.php?action=view&id=2).

4.6 Summary

- The various different metrics produce different relative rankings of historical droughts, but there is a good degree of agreement between the metrics despite their different constructions.
- In general, the results presented here demonstrate a higher prevalence of long droughts prior to 1910, which resonates with previous work which established pronounced changes in the seasonal distribution of rainfall
- The results agree with the major historical droughts identified by Cole and Marsh (2006). These authors provide a more documentary appraisal, whereas the present analysis enables a quantitative summary of long droughts in the study catchments.
- The long droughts generally correspond with extended multi-year periods of below-average precipitation, as demonstrated by long duration precipitation indices. Long droughts also tend to be spatially coherent over large areas, as demonstrated by regional indicators of meteorological and hydrological drought.
- The results also confirm a greater vulnerability to long droughts in the Ely Ouse catchment than in the more responsive Exe. Although the Exe is clearly still vulnerable to multi-year deficiencies, the indicators generally do not pick up droughts lasting more than two years due to the higher within-year variability of flows on the Exe.
- Below average winter precipitation is particularly important in catchments with high storage such as the Ely Ouse where long ‘clusters’ of below-average winter runoff are associated with the major long droughts. Further work should be directed towards exploring the mechanisms associated with the persistence of dry winters and to elucidate the climatological factors associated with inter-decadal variability in rainfall deficiencies.
- The analysis suggests that the most pronounced long runoff deficiencies are from 1800 to 1820, and between 1890 and 1910. The latter period is likely to be more suitable for further study in terms of data availability as there are only a few long rainfall and reconstructed river flow series which extend back prior to 1800. The potential limitations associated with 19th century flow reconstructions must also be borne in mind.
- The indicators used in this project have shown clear value in identifying historical droughts. In general, it is recommended that a range of indicators are used to examine long and/or major droughts in historical records; for example, using threshold methods or DSI to objectively characterise the duration of particular events and using runoff or rainfall accumulations to determine relative severity of contemporary droughts compared with historical episodes.
- For contemporary drought monitoring, rainfall and runoff deficiencies are widely used. There is considerable potential for the application of a version of the Drought Severity Index within drought monitoring, but more work is required to develop the index further; in particular, the sensitivity to

termination criteria should be explored and suitable criteria should be developed for a range of water supply systems

- Previous work has explored anecdotal evidence for impacts of long droughts with a particular emphasis on water resources. In this study, environmental impacts were reviewed in more detail. In long droughts, the most characteristic impact is reduced groundwater levels, with associated low river flows and contraction of the drainage network. This can lead to important hydro-ecological impacts, particularly if the effect of dry winters is exacerbated by combination with warm, dry summers. Only a limited range of information is available from previous droughts; this should be a focus of future monitoring during drought events.

5 Testing of drought management framework

5.1 Methodology

The drought management system was tested for severe historic droughts at workshops for the two catchment case studies attended by staff from the Environment Agency, the water companies and Defra. The methodology (illustrated in Figure 5.1) included:

- several steps in terms of preparing data and models for the workshops;
- interpreting the outputs from the workshops;
- identifying gaps and/or weaknesses in the current drought management system.

During the workshops, water resources models were used to play through two drought scenarios with input from the water companies, Environment Agency and Defra.

Different drought measures, of which most are documented in water company drought plans, were used to manage the water demand and supply balance by the water companies while also taking the impacts on the environment into consideration.

The workshop design is described in further detail in Section 5.2 and the approach taken in the selection of drought scenarios for the two catchments is discussed in Section 5.3.

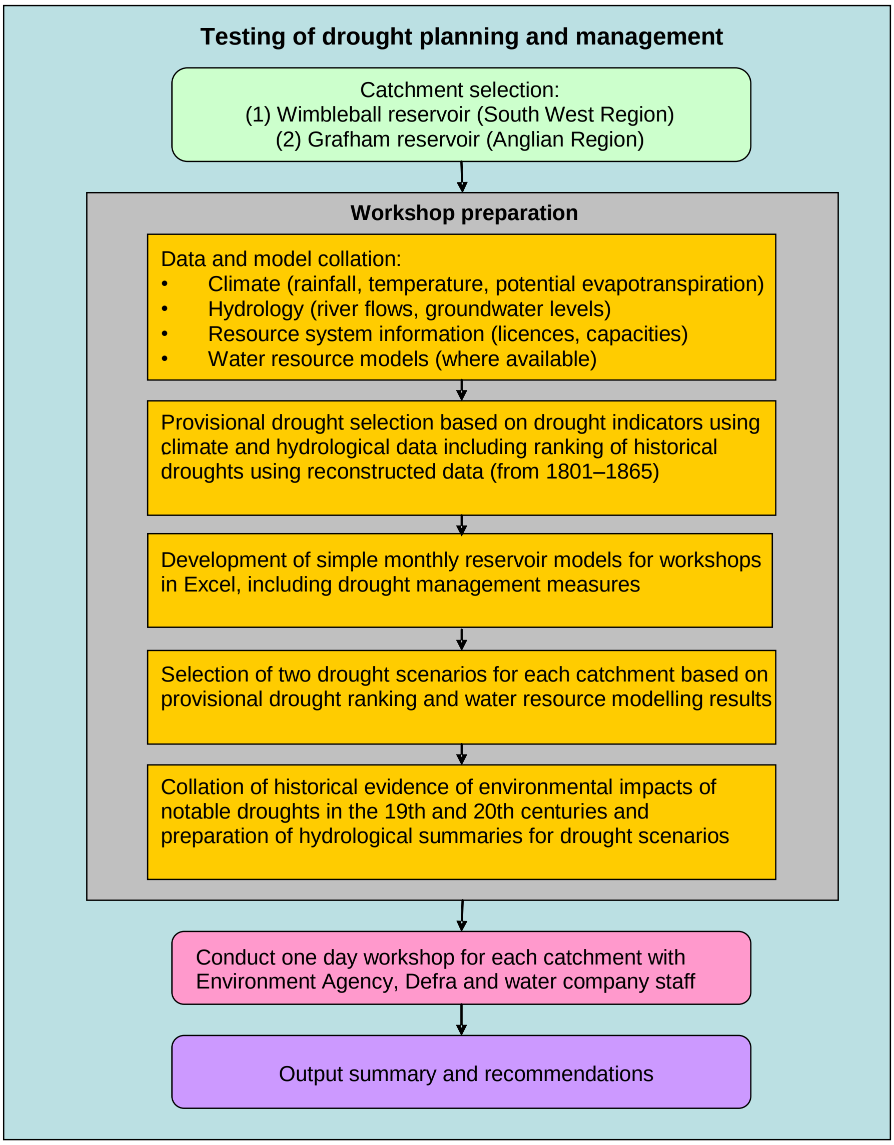


Figure 5.1 Summary of the methodology used for testing the UK drought management system for two selected catchments

5.2 Workshop design

The initial idea for the workshops was to design a form of ‘policy exercise’ – a formal type of ‘strategy game’ often used as a way of thinking through the wider implications of, for example, emergency responses to flood risk and other natural hazards in the UK and elsewhere (Toth 1998). However, given the potential length of the drought scenarios considered in the workshops, it was decided that a simpler ‘game’ in which the players respond to hydrological and water resources data as they emerge and a focus on how this affects decision-making by the water company, Environment Agency and Defra would be more appropriate.

Even this much simpler approach required detailed preparation so that the data presented ‘worked’. Therefore, the model results were presented in such a way that:

- the participants would find it easy to understand and make decisions;
- the scenarios were believed to be plausible by the people involved.

Two simple water resources reservoir spreadsheet models developed for the case study areas based on information provided by the water companies were used for testing the drought management framework interactively.

Additional hydrological information was provided including rainfall, groundwater levels and river flows. This information was presented using the standard classification used by Environment Agency head office in order to provide a context for the droughts and indication of environmental impacts.

Three-month projections using different percentiles of historic monthly flows were presented for a forward look and extended to six months during one workshop. Anecdotal evidence of environmental impacts was also presented for some of the droughts depending on availability.

The droughts selected for the workshop lasted between three and seven years so monthly time steps were used in order to get through the data in the time available.

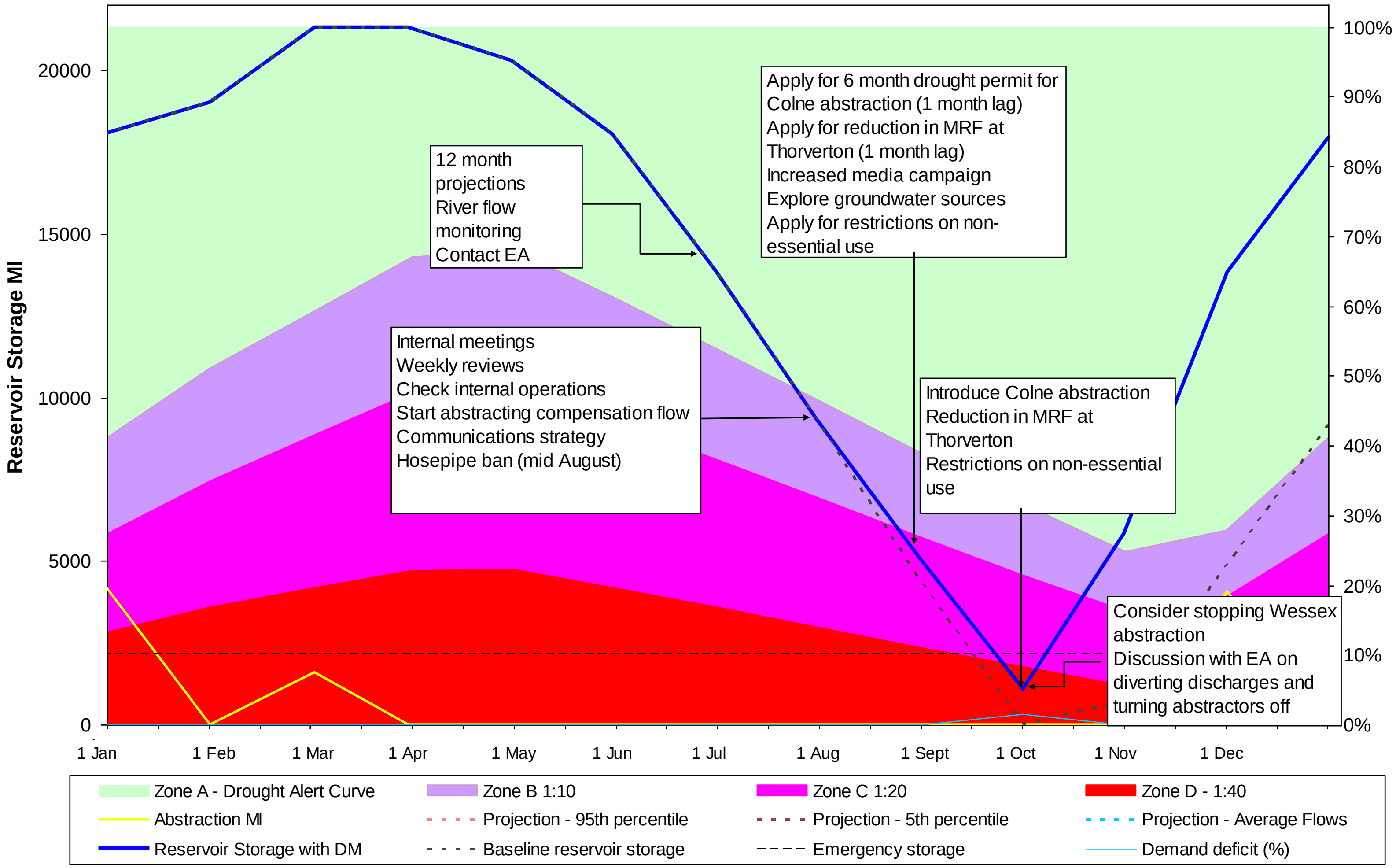
The data (on a graph and a spreadsheet) appeared on a screen that everyone in the room could see (see example in Figure 5.3 for Wimbleball). The time step was operated manually so participants were able to ‘pause’ the model in order to explore and capture a decision point. Thus the data emerged at different speeds at different times. Environment Agency and Defra representatives, on the whole, waited to hear from the water company people and responded to their proposed actions – although all the groups present were able to speak at any time.

Decisions or reflections that emerged through the game were captured in writing at various intervals and particular drought measures were included in the water resources models. Four different levels of capture and evaluation were included:

- individual drought interventions (by the water company, Defra or Environment Agency);
- annual reviews of the ability to manage the drought situation and future concerns;
- scenario debriefs (summary and discussion after each of the two drought scenarios);
- overview of the day.

The workshop design is described in further detail in Appendix G, which also includes general guidelines on running this type of drought management exercise.

An example of actions taken during the workshop with South West Water for Wimbleball reservoir for one drought year is illustrated in Figure 5.2. This shows the reservoir drawdown with and without restrictions, and illustrates the effect of various drought management measures implemented by the water company during the workshop.



12 month projections
River flow monitoring
Contact EA

Apply for 6 month drought permit for Colne abstraction (1 month lag)
Apply for reduction in MRF at Thorverton (1 month lag)
Increased media campaign
Explore groundwater sources
Apply for restrictions on non-essential use

Internal meetings
Weekly reviews
Check internal operations
Start abstracting compensation flow
Communications strategy
Hosepipe ban (mid August)

Introduce Colne abstraction
Reduction in MRF at Thorverton
Restrictions on non-essential use

Consider stopping Wessex abstraction
Discussion with EA on diverting discharges and turning abstractors off

Figure 5.2 Example of drought actions taken during the workshop for Wimbleball reservoir

5.3 Selection of drought scenarios

Two droughts with different characteristics were selected for each of the two case studies to allow exploration of a wide range of possible actions and responses as these will depend on the onset, timing and duration of the droughts.

The main aim of the drought scenario selection was to identify periods suitable for testing the two systems on different more severe, multi-seasonal droughts than experienced in recent times and more significantly outside the normal period used by water companies for drought planning purposes (normally 1920–2006).

The selection of the historical droughts was kept from the participants to prevent prior knowledge from affecting the decision-making process.

5.3.1 Wimbleball

For the Wimbleball system, the pumped storage scheme designed to refill the reservoir every winter means that droughts can essentially be treated as single year events. Running the simple water resources model for the period from 1865–2006 indicates that the reservoir is always close to 100 per cent full on 1 April. This assumes different levels of demand ranging from 131–155 Ml/day, which is considered a realistic estimate. Demands are currently lower and within the design capacity of the reservoir.

Because demands are lower, in reality the reservoir may not always be completely filled over the winter as pumping is expensive and it may be decided to aim for a slightly lower storage level while ensuring that supplies will not be put at risk. Furthermore, the use of a monthly time step in the simple model will smooth out the reservoir response to some degree and it is therefore likely in the model that the capacity would not always reach 100 per cent. However, overall the modelling indicates that the pumped storage is very effective in dealing with multi-seasonal droughts and the system is mainly at risk during very dry summers.

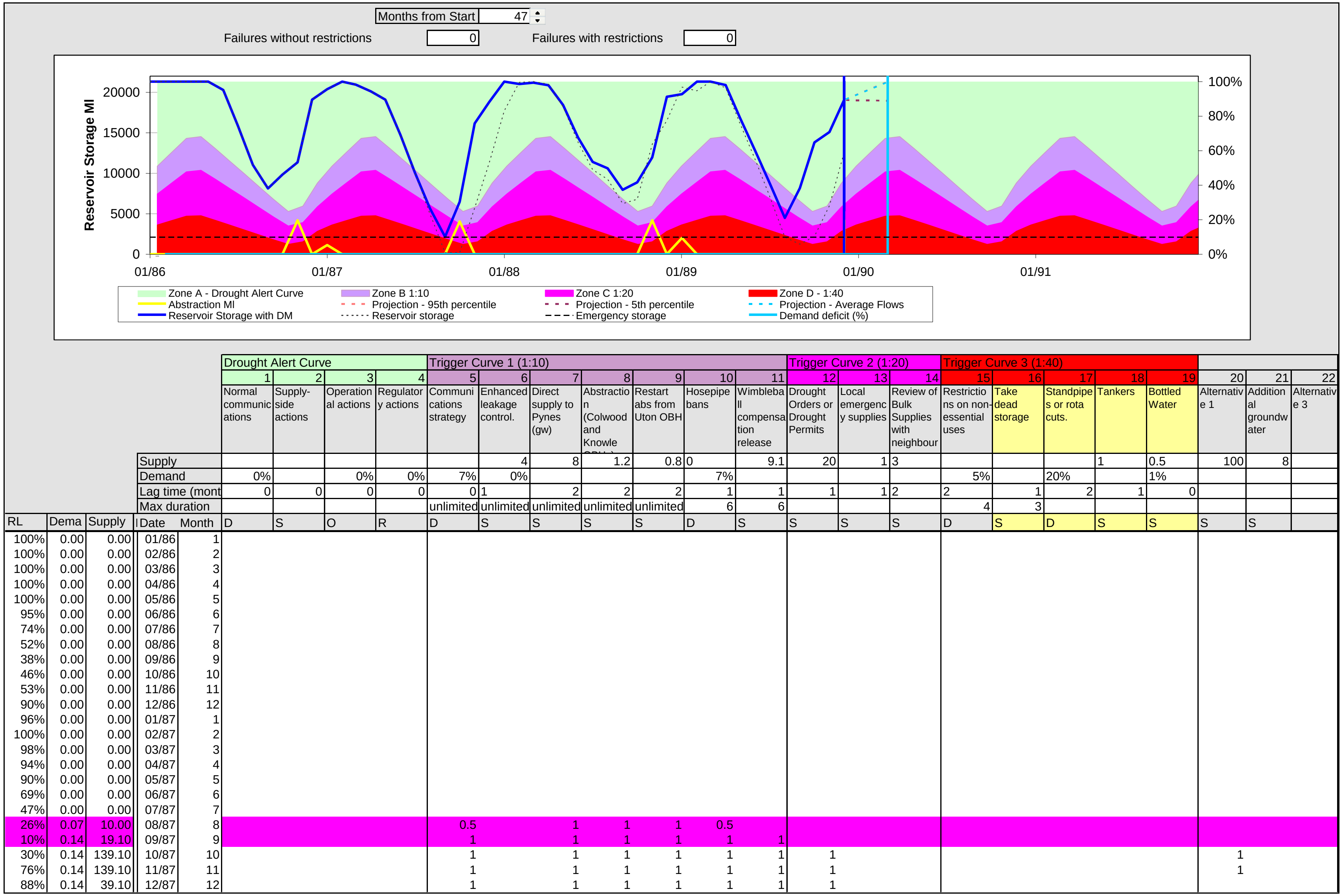
Drought indicators calculated from long-term climate and river flow time series for the period 1865–2006 identified four drought periods of particular severity:

- 1887–1888;
- 1901–1907;
- 1895–1898;
- 1869–1870.

In terms of reservoir drawdown, the simple monthly model indicates that from a water resources perspective the droughts of 1869–1870, 1887–1888 and 1895–1898 were the most severe. The droughts of the early 20th century were not significant in terms of reservoir drawdown, probably due to more variable rainfall and resilience of the system to winter droughts.

For the workshop the following two periods were selected:

- 1868–1871;
- 1886–1887 + 1895–1896.



Months from Start 47

Failures without restrictions 0

Failures with restrictions 0

					Drought Alert Curve				Trigger Curve 1 (1:10)							Trigger Curve 2 (1:20)			Trigger Curve 3 (1:40)							
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
					Normal communications	Supply-side actions	Operational actions	Regulatory actions	Communications strategy	Enhanced leakage control.	Direct supply to Pynes (gw)	Abstraction (Colwood and Knowle	Restart abs from Uton OBH	Hosepipe bans	Wimbleball compensation release	Drought Orders or Drought Permits	Local emergency supplies	Review of Bulk Supplies with neighbour	Restrictions on non-essential uses	Take dead storage	Standpipes or rota cuts.	Tankers	Bottled Water	Alternative 1	Additional groundwater	Alternative 3
			Supply							4	8	1.2	0.8	0	9.1	20	1	3				1	0.5	100	8	
			Demand		0%		0%	0%	7%	0%				7%					5%		20%		1%			
			Lag time (mont		0	0	0	0	0	1	2	2	2	1	1	1	1	2	2	1	2	1	0			
			Max duration						unlimited	unlimited	unlimited	unlimited	unlimited	6	6				4	3						
RL	Dema	Supply	Date	Month	D	S	O	R	D	S	S	S	S	D	S	S	S	S	D	S	D	S	S	S	S	
100%	0.00	0.00	01/86	1																						
100%	0.00	0.00	02/86	2																						
100%	0.00	0.00	03/86	3																						
100%	0.00	0.00	04/86	4																						
100%	0.00	0.00	05/86	5																						
95%	0.00	0.00	06/86	6																						
74%	0.00	0.00	07/86	7																						
52%	0.00	0.00	08/86	8																						
38%	0.00	0.00	09/86	9																						
46%	0.00	0.00	10/86	10																						
53%	0.00	0.00	11/86	11																						
90%	0.00	0.00	12/86	12																						
96%	0.00	0.00	01/87	1																						
100%	0.00	0.00	02/87	2																						
98%	0.00	0.00	03/87	3																						
94%	0.00	0.00	04/87	4																						
90%	0.00	0.00	05/87	5																						
69%	0.00	0.00	06/87	6																						
47%	0.00	0.00	07/87	7																						
26%	0.07	10.00	08/87	8					0.5		1	1	1	0.5												
10%	0.14	19.10	09/87	9					1		1	1	1	1	1											
30%	0.14	139.10	10/87	10					1		1	1	1	1	1	1								1		
76%	0.14	139.10	11/87	11					1		1	1	1	1	1	1								1		
88%	0.14	39.10	12/87	12					1		1	1	1	1	1	1										

Figure 5.3 Example of model interface and drought actions for drought scenario 2 for the Wimbleball reservoir model

The first scenario essentially consists of a warm-up period and then two summer droughts. The severity of the summer droughts is comparable to the more recent droughts in 1919–1921 and the droughts are more severe than the droughts of 1976 and 1990–1991.

The second scenario was constructed using data from two different periods and the modelled drawdown for two of the years is slightly more severe than modelled drawdown in 1990–1991, 1995 and 2003.

Due to the smoothing of modelled reservoir levels as a result of using monthly data (especially during the summer months when fish bank abstraction is taking place over a few days), the demand was set higher than normal demand (150–155 Ml/day). This produced a drawdown close to that observed using daily data.

5.3.2 Grafham

For Grafham reservoir, multi-seasonal droughts and especially winter droughts are more severe than for Wimbleball. However Grafham is less affected by single year events than Wimbleball.

Drought indicators calculated from long-term climate and river flow time series for the period 1800–2006 identified three drought periods of particular severity:

- 1803–1809;
- 1815–1817
- 1894–1904 (wet winters in 1896–1897 and 1899–1900).

In terms of reservoir water level drawdown, the droughts of the early 20th century do not seem particularly severe in line with the results for Wimbleball.

Some of the river flow data in the latest version of the Grafham model have been changed somewhat following quality checks and using a new transposition from Denver sluice to Offord in order to reproduce the drought yields presented in Anglian Water’s current drought plan. Therefore, the recent results differ from those presented in the earlier ‘severe’ droughts project.

The most severe droughts in water resources terms occur during the period in the early 1800s and 1815–1816. Although the 1800–1810 falls within the ‘Little Ice Age’ when temperatures were a degree lower, the drought is still assessed as suitable for illustrating possible drought conditions.

For the workshop, two scenarios were constructed based on a combination of these two drought periods. The first drought scenario is a combined drought based on 1807–1808 and 1815–1817, and the second scenario covers the 1801–1804 drought.

The first drought is considerably more severe in terms of both length and reservoir drawdown than observed in recent times such as during the 1934–1935 and 1976 droughts. The same applies to the second scenario which illustrates a less prolonged but very severe water resources drought.

The demand used was set to 262 Ml/d due to smoothing of the results using monthly data, the likelihood of increased demand during droughts, and to stress the system. This is slightly higher than normal operations at Grafham, but equal to the deployable output with demand restrictions presented in Scenario 3 of the company’s drought plan (Anglian Water 2008). The implications of using a slightly higher demand for the supply–demand balance and the ability to manage the drought were discussed in the context of having an allowance for target headroom in the supply–demand balance for water resources planning during the Grafham workshop.

5.4 Overview of workshop findings

The drought management framework – including supply and demand side measures and communications between the companies and Government – worked well for drought events within ‘normal experience’ or the ‘design criteria’ of existing drought plans, but was challenged by more severe water resources droughts. Public water supplies were maintained in all the drought scenarios tested, but there were consequences for the environment, agriculture and other water users. There was a requirement for voluntary reductions in industrial demands in the case study for Grafham.

In all the drought scenarios considered, there was a balance between demand and supply side measures implemented. In addition, different operational approaches were taken to ‘squeeze’ further outputs from existing supplies.

As each drought became more severe, more imaginative measures had to be put in place including measures outside the respective drought plans.

There was a reluctance to place hosepipe bans on customers and a tendency to ‘hold the line’ until these were absolutely necessary.

The issue of following the defined control rules using a principle of just-in-time or adopting a more precautionary approach in the real event came up in both workshops (discussed in more detail in Section 5.4.2).

The use of standpipes and rota cuts was seen as unacceptable and sign of failure of the water resources system.

Tables 5.1 and 5.2 summarise the measures implemented for the Wimbleball and Grafham scenarios.

Table 5.1 Wimbleball: measures implemented – headlines with Ml/d for worst year in each scenario (main points in bold)

	Scenario 1 High demand with 1868–1871 drought	**Scenario 2 High demand with 1886–1887 plus 1895–1896 drought**
Drought characteristics	• Three dry years with successively drier summers/autumns • Rapid ‘speed of onset’/drawdown • Years 1 and 2 within company experience but **Year 3 was ‘unprecedented’**	• Four dry years with a severe drought in years 2 and 4 • Rapid onset with short winter periods with full reservoir stocks • **Outside company experience**, particularly years 2 and 4 which required wide-ranging drought management measures
Supply	• Significant additional supplies needed for 2–3 months in third autumn • **Used emergency measures outside drought plan**	• Significant additional supplies needed in year 2 • Further supplies needed for two months in year 4 • **Used emergency measures outside drought plan**
Demand	• Hosepipe ban used • 15% reduction in demand	• Hosepipe ban and restrictions on non-essential use • Tried to reduce Wessex Water’s demand – possible drought order • Potential for temporary licences to speed up response • 19% reduction in demand
Operational	• Use of monitoring, projections, liaison communications, leakage reduction • **Questioning drought trigger approach – need methods for including these events in drought planning**	• Use of monitoring, projections, liaison communications, leakage reduction, re-zoning • Much better working with Environment Agency and other regulators • **Importance of hydrological reporting and use of drought projections highlighted**
Other issues	• **Supplies seriously threatened in third year of drought** • **No public water supply failure** • Main environmental concern related to fisheries and operation of ‘fish bank’ • **Drought management framework worked effectively in Years 1 and 2 but tested in Year 3 – the water company had to use emergency measures outside its drought plan** • National political interest	• **Supplies seriously threatened over several years** • **No public water supply failure** • **Some drought powers, e.g. hosepipe ban could have been used earlier in year 4** • Main environmental concern related to fisheries and environmental impacts year-on-year with two severe drought episodes • **Drought management framework tested to breaking point – measures used outside plan to maintain supplies** • Defra concerned/asked whether water resources management system is flawed. • National political interest and review of drought management framework

Table 5.2 Grafham: measures implemented – headlines with Ml/d for worst year in each scenario (main points in bold)

	Scenario 1 High demand with drought based on 1807–1808 to 1815–1817	**Scenario 2 High demand with 1801–1804 drought**
Drought characteristics	• Long drought lasting almost five years and punctuated by very dry November to April periods which are important for reservoir refill • Individual hydrological drought episodes were no more severe than 1921–1922 or 1933–1934 or 1976 drought periods • Hydrological drought with high demands (262 Ml/d) created difficult water resources management conditions	• Long drought with high demand (262 Ml/d) – most severe water resources drought for 200 years – causing rapid unprecedented drawdown of Grafham • **Drought outside the range of normal company experience – how to include these in drought planning? Recalculation of DO for WRMP could be necessary.**
Supply	• Operational improvements • Required balancing across zone – use of WRMP headroom • **90 Ml/d including MRF reduction** (70 Ml/d plus 20 Ml/d from Rutland)	• Operational improvements • Required balancing across zone – use of WRMP headroom • Emergency plant – effluent re-use • Operation Rodeo flow reversal • **139 Ml/d including schemes that are not included in drought plan** (30 Ml/d from Rutland, Foxcote reservoir 7 Ml/d, MRF reduction 70 Ml/d, industrial savings 7 Ml/d, emergency supplies 15 Ml/d and Operation Rodeo 10 Ml/d)
Demand	• Hosepipe ban • Voluntary reductions • **13% reduction**	• Hosepipe ban • Voluntary reductions • Non-essential use reductions • **19% overall demand reduction**
Operational	• Rutland used to balance supplies • Leakage control • Benefit of using available headroom / outage allowance	• Wing WTW used to balance supplies with available headroom • Leakage control • Benefit of using available headroom/outage allowance
Other issues	• Environmental impacts on Ouse Washes – risk of infraction proceedings • Refusal of MRF reduction at Offord until non-essential use granted • Spray irrigation and agricultural restrictions introduced by the Environment Agency in collaboration with the farmers to reduce environmental impacts	• Speed of onset of drought challenging for water company and would have been problematic had the reservoir failed • Spray irrigation and agricultural restrictions introduced by the Environment Agency in collaboration with the farmers to reduce environmental impacts

5.4.1 Communication with the public

Communications with the public and special interest groups through the media and direct contact were seen as a key priority for water companies and the Environment Agency during a drought. It was perceived that this would take up significant resources in terms of people's time (media training, interviews, preparing messages and materials, etc.) and the organisation's resources.

It was agreed that getting the message right was a vital part of the process of good drought management. There was concern about how to walk a line between being alarmist and requests for significant demand reductions. It was understood that there were important 'signals' that a drought was in progress that helped to 'warm people up' to the idea of a hosepipe ban. Other measures such as increased leakage control were seen as important to show that the changes in behaviour that the public were making were not perceived to be lost to leakage in the company's supply network.

The communication of 'in extremis' measures was another major concern for the water companies. Companies felt that these potentially controversial measures with a low probability of ever being needed would be difficult to present in company drought plans, which require full public consultation. It is hard to communicate measures that would in normal circumstances seem unthinkable but which, in an extreme situation, have to be considered to prevent the severe consequences of the failure of public water supply. Further work is required to determine where to draw the line in terms of extent of measures included in the drought consultation process.

There were thoughts about how supportive and understanding the public were likely to be. Despite initial reluctance to impose hosepipe bans and other demand restrictions, it was felt in one of the workshops that, as the drought progressed and the severity increased, the public would be 'better educated' and that there could be a banding together and a 'Dunkirk spirit' might prevail – although it was also said that it could equally be a spirit of anger and frustration.

5.4.2 Liaison between the water companies, Environment Agency and Defra

Although the three organisations had different motives and core purposes, there was a general acceptance that, in an extreme situation, essential public water supplies should be maintained and ultimately that this might be in preference to the environment by allowing emergency measures to abstract more water.[10]

In the workshop for Grafham reservoir, Environment Agency participants expressed some concern about how to communicate this publicly. On one level they would want to reassure the public that public water supply was safe but also, to reduce impacts on the environment, that water should be used sparingly. There was a sense from Environment Agency participants that the emphasis on public water supply had gone too far and it should perhaps be shifted back in favour of the environment.

Overall, there was a reluctance from water companies to bring in measures that were perceived to be unpopular with the public, e.g. hosepipe bans or restrictions on non-essential use.

There was a sense (expressed more strongly in the workshop for Wimbleball) that:

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[10] One comment about 'sharing the pain' expressed in one workshop provides an alternative view. From this perspective, the public is supporting the water companies to manage the water resource and the impacts on the environment would be 'shared'.

- in a drought there would be a ‘we’re all in this together’ attitude prevailing;
- the Environment Agency and water companies would band together to work out the best strategies.

Personality, experience, institutional memory and rapidity of staff turnover may have an important part to play in building these effective links (and more intangible elements such as ‘respect’ and ‘trust’) between the different players. They could become very important when it comes to a drought situation where there is uncertainty about what is going to happen. Believing that the other parts of the system are doing the best they can and allowing room for constructive negotiation during drought (e.g. in terms of annual reporting) may make a big difference to how well the drought is managed – and the level of recriminations and blame after the event.

In both workshops the need was mentioned to educate others in the three organisations who do not work directly with drought. This was important so that they would:

- understand the knock-on effects of drought for their work;
- be primed to understand how resources in the organisations might have to shift, especially if the drought was prolonged.

Water companies expressed some frustration about the legislative procedures required to apply for drought orders and drought permits, and confusion about how they differ (which may require clarification). There was also discussion on what could be done in advance of an application for a drought order or drought permit to ensure a smooth application process that avoided rejections at public hearings.

5.5 Performance of existing drought system

The drought management framework, including supply and demand side measures and communications between the companies and Government, worked well for drought events within ‘normal experience’ or the ‘design criteria’ of existing drought plans but was challenged for more severe water resources droughts. In all cases, measures were taken to maintain public water supplies and there were no failures of public water supply – though failure was avoided only through some significant supply interventions.

The hydrological drought events used in the workshop were different from, but not always more severe than, the 1921–1922, 1933–1934 and the 1976 droughts used by the water companies for planning purposes. In the workshops, these events were combined with high demands making it difficult to manage the supply–demand balance.

In the Grafham example, water managers aimed to meet the high demand by using resources from an adjacent larger reservoir system with the implicit assumption that the water resources drought was not as widespread in other parts of the water company area. However it is likely the entire water resources system would have been affected in the drought chosen for the workshops, so the resources available were likely to have been overestimated. Anglian Water was confident that headroom could be used for providing additional water from other parts of the catchment, e.g. from Wing WTW (Rutland) to Grafham. But if the drought was very widespread, it is uncertain whether sufficient headroom would in fact be available.

The ‘speed of onset’ and fast pace at which water resources drought developed for the more severe events cause difficulties in terms of:

- early recognition of a potential threat to water supply;

- the time taken to implement measures due to operational and legal constraints (particularly for the Wimbleball example).

The close linkages between water resources planning and drought planning were evident throughout the discussions. There was, arguably, an over-simplified view that WRMPs and drought permits must be entirely consistent in terms of design conditions on demand and deployable output. This may have contributed to the need to use measures outside the drought plan for some of the workshop scenarios.

5.6 Gaps and potential improvements

Common themes from both workshops included:

- how water companies should manage drought risks;
- whether the drought framework or water companies are risk averse and how these issues impact on drought planning;
- what water companies and the Environment Agency need to cover in their respective drought plans.

5.6.1 More guidance

There was a request for more explicit guidelines on how far to go into extreme droughts in water company drought plans. As companies become more risk averse (by increasing DO and headroom as part of the WRMP process or avoiding drought restrictions), systems are likely to fail less frequently but, when they do, the failure can have dramatic consequences.

5.6.2 ‘In extremis’ measures

Linked to this discussion was the communication of ‘in extremis’ measures, i.e. measures that would in normal circumstances be unacceptable but which in a prolonged, severe drought might become necessary to avoid the consequences of failure in the water supply system.

Participants at both workshops expressed concern about how the public and special interest groups would react to ‘in extremis’ measures if these were detailed in the drought plan as they are controversial and the likelihood of needing them very low There was a sense that the potential use of such measures should, at least, be mentioned in the drought plan as secrecy may make drought permit and drought orders more difficult in the event of a severe and long drought situation.

5.6.3 Emergency measures

The question of how to present innovative ideas/emergency measures for the ‘worst case’ low probability events was raised at both workshops. At the moment there is no clear request that such measures should be included in drought plans. However, there could be a section that covers ‘low probability, worst case’ scenarios in which emergency measures could be outlined and the low probability highlighted, i.e. it is very unlikely these measures would ever be used.

5.6.4 Need for flexibility in the planning system

It was clear from the workshops that interventions in droughts do not play out as ‘neatly’ as it might appear from the drought plan. Compromises and ‘horse trading’ were played out in the scenario games and subsequent discussion suggested that this was how interactions and interventions actually play out in a real drought. There is a need for flexibility in the planning system to allow for this, but this is difficult to communicate in the drought plan.

There needs to be a balance between transparencies of potential interventions (e.g. clear information about what the water company is planning and accountability) without increasing the burden of paperwork and over-elaborate processes that divert attention and further stretch the limited staff resources and time available to respond during severe droughts.

5.6.5 Headroom

Headroom, which is used in water resources planning to deal with uncertainties and risk, was perceived in one workshop as being available or partially available for contingency use during a drought.

Target headroom is used in supply–demand balance planning as a margin to allow for risk and uncertainty, and together with the outage allowance, is used in the measurement of security of supply. It would be unrealistic to expect a supply system to be operating without a margin of available headroom (including outage) between deployable output defined by reservoir yield and forecast/actual demand.

Uncertainty and risk in drought planning is dealt with through the allowance of 30 days emergency storage for reservoir systems.

In zones where the consequences of severe drought are high, there may be a requirement to provide spare capacity through drought planning or water resources planning but, for drought planning, this is a separate issue to headroom calculations.

5.6.6 Risk of outage

The risk of outage during drought was also raised at the workshops. It was suggested that to really test the system it would be good to have a severe drought and an ‘outage’ event. In reality, any outage during times of drought would be dealt with very quickly as all resources would be required at or close to full capacity. Nevertheless, a combined drought and outage scenario may provide a worthwhile test for drought plans, keeping in mind that the combined probability of this event will be low.

5.6.7 System improvements

At the South West Water workshop it was suggested that, in the middle of a drought, the Environment Agency should not expect companies to fulfil all the normal requests for forms and procedures required for certain applications as these were too resource consuming and the matters were too urgent (‘the legislation takes too long’).

There were discussions about how the system might be simplified, for example:

- unifying the drought permit and drought orders requests (or at least clarifying how they worked as there was confusion about this);

- pre-arranging access with land-owners to avoid having to use drought orders (drought orders can authorise access, drought permits can not);
- obtaining temporary licences in place of drought permits and drought orders.

It was suggested that water companies could put effort into ‘smoothing’ the progress of applications for drought orders and drought plans in anticipation of them being needed. Those who might object could be contacted before the application was made so that any objections could be dealt with in advance. When it was needed the application might then go through unimpeded or at least attract fewer objections. Concerns were raised by Anglian Water that this would not work in practice and that a better solution would be to vary abstraction licences based on triggers, for example, so that hands-off flow is reduced when a drought trigger is reached. This is the ‘mirror image’ of licence conditions that reduce groundwater abstractions during drought.

There was a sense in both workshops that the current system does not provide incentives for early use of demand restrictions. In the scenario game, there were demand reduction measures described in their drought plans that the water companies could have used before they requested a drought order or drought permit. These measures would have been favourable for the environment but perceived as less acceptable by the public. One comment at the South West Water workshop was that ‘the precautionary principle was used to protect public supply but not the environment’. It was communicated that, in the future, there would be more powers for water companies to impose demand reductions.

Overall there is a need to move to an improved ‘drought risk management’ approach where:

- risks (probability × consequences) are clearly understood;
- a range of flexible drought planning and/or water resources planning measures are implemented.

If the consequences of severe longer droughts include high economic, social and environmental costs, the case for increased resources or different levels of service could be made. Scenario testing workshops using historic droughts and using this approach could be applied more widely in water companies (in collaboration with Defra and Environment Agency) to test the robustness of existing drought management processes.

5.6.8 Data quality

Improvements to the quality of data provided by the Environment Agency were discussed at one of the workshops. Hydrological data based on the Environment Agency’s categories (i.e. normal, below normal, etc.) were found to be very useful (the workshop scenario used data provided by CEH which incorporated this method). There may be a need for Environment Agency regions and areas to have plans in place to move to weekly reporting using head office’s weekly river flow reporting method.

The workshops also highlighted the benefit of using hydrological projections to take a forward look at risk of reservoir drawdown. Although there may a longer term potential in using Met Office weather predictions, there was a more immediate need to improve flow forecasting methods using simpler rainfall and flow projection techniques.

6 Recommendations

Based on the workshop findings and further discussions with the steering group, the project team identified a number of gaps in the current understanding of long droughts that could be addressed through improvements to drought guidance as well as further research.

Overall, the drought management framework in England and Wales appears to work well with clear roles and responsibilities for Government, water companies, the Environment Agency and water customers during periods of drought. In the project workshops, water supplies were maintained for the case studies with significant demand restrictions and supply-side measures throughout several years of major droughts. Nevertheless, some of the drought events considered were outside the range of water company experience and presented difficult operational decisions related to water supply, meeting customer expectation and the environment.

One of the main outcomes of the workshops was the requirement for water company drought plans to be useful, flexible and practical tools that:

- cover all the drought management processes and measures applied during periods of drought;
- present potential impacts and management measures in a clear and transparent way to water customers and other stakeholders.

Consequently, many of the recommendations are aimed at reinforcing or refining existing drought planning guidance in order to improve drought risk management by the water companies and the Environment Agency.

6.1 Drought planning guidance

The following recommendations for improving current drought planning guidance were identified:

- **Drought planning guidance should emphasise the importance of adhering to drought plans, including introduction of demand restrictions during the early stages of a drought.** The workshops indicated some reluctance by the water companies to introduce demand restrictions including enhanced communication, hosepipe ban and non-essential use bans at various stages of drought even when different triggers were hit despite such measures being in water company drought plans. Clearly, operational decisions were based on a wide range of information such as time of year (winter/summer), situation in adjacent resources zones and actions of other water companies, customer expectations and reputation risks. While the ability to consider many factors and take a flexible approach is the strength of the drought management system, there should be no disincentives for water companies taking action during severe drought, e.g. enhanced communications for voluntary reductions and the timely use of hosepipe bans. Guidance should also encourage intervention in non-household demand during extreme drought, including using financial incentives. Further research is needed on the barriers to using available demand measures by the water companies in a timely manner such as Overall Performance Assessment (OPA) scores and public opinion (see recommendations for research in Section 6.2).

- **Drought planning guidance should stress the importance of including all possible drought measures in water company drought plans.** Drought plans should be viewed as flexible and practical documents which reflect the full range of measures and actions that may need to be taken by the water companies during different stages of a drought. The workshops indicated that a number of measures used in extreme events are not currently included in drought plans, although some of these were well-established with either previous experience of using the option or as internal contingency plans. Furthermore, particular drought measures were not introduced at the stages currently indicated in the plans. Further work is needed to clarify how drought measures will be implemented during extreme droughts and how to present measures used only in extreme circumstances in the plans (e.g. using probabilities). The communication of low probability, high consequence droughts and the measures needed to maintain supplies in such events is an area that requires further research (see recommendations for research in Section 6.2).

- **Drought planning guidance could be improved to encourage water companies to prepare for drought permits and drought orders well in advance of drought periods.** It is recommended that the water companies are reminded that the investigations required for drought permits and drought orders including environmental impact assessments and monitoring plans can be undertaken prior to droughts in order to speed up the application process when these are required. The workshops illustrated that the lag time from application to implementation could be a significant problem with regards to managing drought. Early preparation of the Environmental Impact Assessment (EIA) and monitoring plan as well as liaison with the Environment Agency would, it is estimated, speed up the application process from 4–6 weeks to 1–2 weeks. The need for further joint Environment Agency/Defra guidance to clarify the difference between drought permits and droughts orders was also identified at the workshops.

- **Further guidance is needed on how to test the sensitivity of water company drought plans to different kinds of drought, including more extreme events not currently considered in the plans.** Improved methods are needed to test drought planning under more extreme drought conditions. A range of different approaches could be considered from simple sensitivity testing to detailed hindcasting and modelling studies and workshop exercises depending on the ‘robustness’ of existing plans (see Appendix F for methods on hindcasting climate data and Appendix G on drought workshop design). Any future guidance should be flexible, allowing for the use of different methods and should consider droughts of different severity, lengths and spatial extent. Potential methods for hindcasting and drought workshop methods are outlined in Appendices F and G. There should also be guidance on how water companies should respond if systems prove difficult or impossible to operate during exceptional droughts.

- **Further work is needed on how to provide earlier recognition of drought through the use of different triggers (e.g. high demand or speed of recession indicators) to enable water companies and the Environment Agency to take timely actions to manage drought.** Water companies currently use reservoir trigger curves and reservoir levels from recent drought events (e.g. 1976 or 1990) to assess the severity of a drought situation. Guidance could be improved to encourage water companies to use average drawdown curves or range of normal behaviour (levels, rates of fall) to identify unusual reservoir behaviour and present these in their drought plans. Multi-variate triggers could potentially also be used to provide earlier warnings than current reservoir triggers (see recommendations for research in Section 6.2). An example of modelled drawdown for Wimbleball reservoir for 1870 is shown in Figure 6.1 including modelled average reservoir drawdown for the period (1955–2006) and drawdown in 1976. This illustrates that some reservoirs have been designed to drop to fairly low levels during the summer period.

- **Improvements to the current water company understanding of risk factors for resource zone demand-supply balances are needed.** Drought planning guidance could be improved to require an assessment of vulnerabilities of resource zones to different types of drought and combined risks, e.g. outage during periods of drought. The workshops indicated that different zones and types of systems respond very differently to droughts and this should be considered in water resources and drought planning. The use of pumped storage can, for example, produce a very reliable water resources system under a range of conditions but the system may fail dramatically under very severe drought conditions, e.g. 200-year drought or one with very different characteristics to the droughts used for design purposes.
- **Drought planning guidance on the use of temporary licences in place of drought orders is needed.** The use of temporary licences is not currently covered in drought planning guidance and the workshops indicated that there is some confusion about the practical uses of temporary licences among both the water companies and within the Environment Agency. The Environment Agency has indicated that some minor changes are required to the current licensing system to enable water companies to apply for temporary licences. In some circumstances this could be a useful alternative to applying for drought orders, which tend to be more time-consuming and costly.

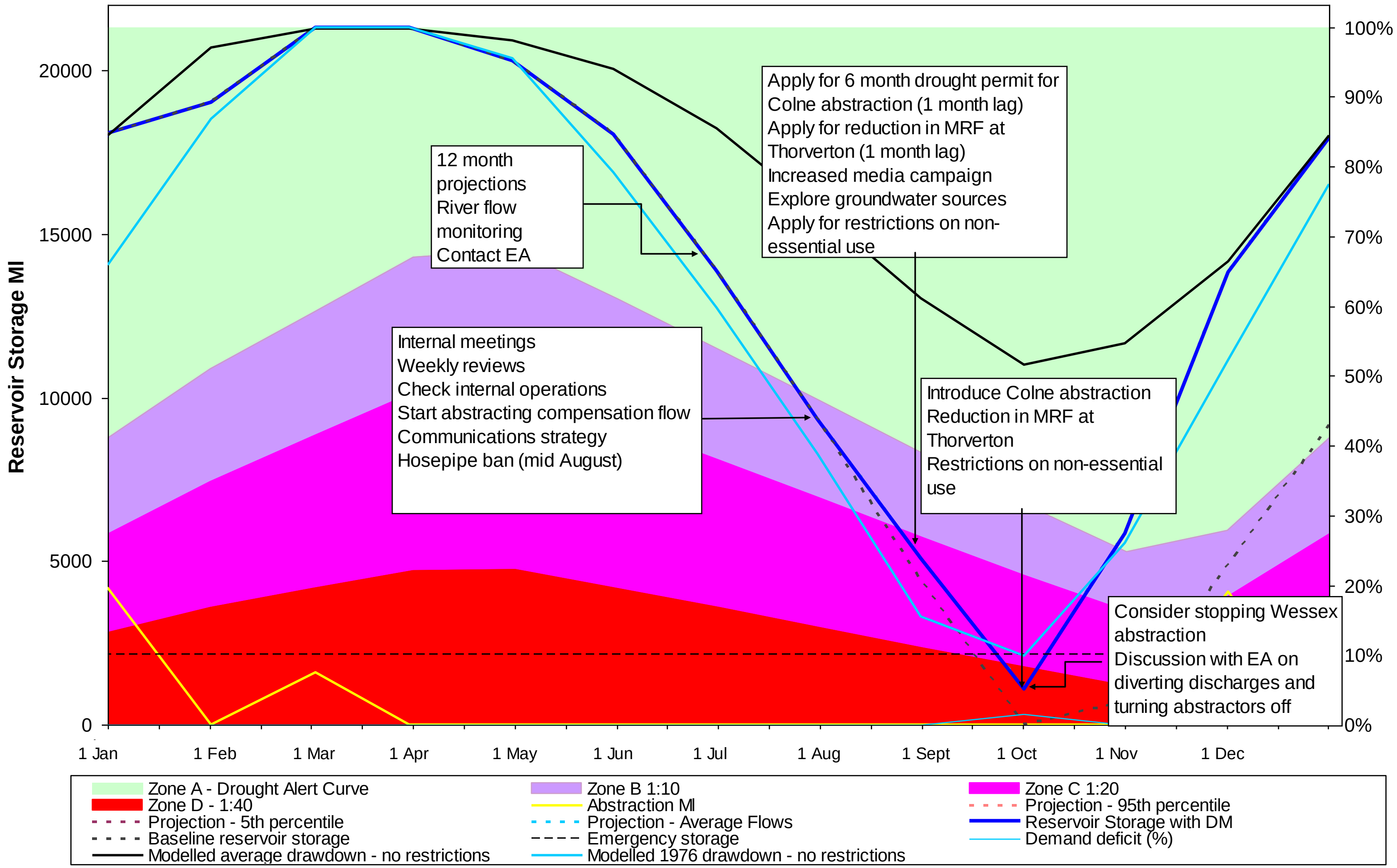

Figure 6.1 Illustration of Wimbleball reservoir behaviour under average and drought conditions (1870 and 1976)

6.2 Further research

The following research recommendations were identified based on the workshop findings:

- **Further research into improved flow forecasting methods including use of medium range weather predictions is recommended.** While there is long-term potential in numerical weather prediction (NWP) and medium to long range forecasts, the workshops indicated a more immediate need to improve flow forecasting methods using simpler scenario-based rainfall and flow projection techniques.
- **Further investigation on how to present and communicate very low probability and high consequence drought events to the public, including the measures that would be needed to maintain water supply.** The water companies expressed concerns about presenting very extreme events or interventions in their drought plans to the wider public. There is a need to establish the benefits/drawbacks of presenting information about extreme interventions in severe drought to the public and to determine whether water company concerns are valid or whether public perception could be improved by more transparency. A better understanding of the attitudes of the public and water customers to drought management is required.
- **Research is needed on barriers within the water companies to introducing demand-supply measures in a timely manner.** Investigations into the barriers within the water companies to introduce various demand and supply measures in a timely manner would be beneficial. This could include investigating the influence of measures such as OPA scores and public opinion on drought management actions. It is not currently clear whether there are significant barriers, what they are or how they may be affecting water company decisions during droughts.
- **Water companies could benefit from further research on development and use of multi-variate triggers.** The workshops highlighted the need for earlier recognition of severe or unusual behaviour of water resources systems. Multi-variate triggers could be considered looking at not just rate of decline in reservoir levels, but also demands and perhaps river flow forecasts and temperatures.
- **Further research/investigations are needed with respect to environmental needs during severe droughts.** The workshops indicated that it was very difficult to decide on the timing and magnitude of interventions needed to protect fisheries and the environment based on the available information.
- **Research is needed on the environmental and other consequences of drought.** Further information on the consequences of droughts including collection of further anecdotal evidence from historical studies is required to develop a better understanding of the environmental consequences of droughts, how to better protect the environment, and how to encourage environmental recovery following a drought.
- **Research into the modes of failure for different types of water resources systems.** The two systems used in the workshops proved very robust under a range of hydrological conditions, but when severe drought

did ‘break’ the system, maintaining supply was difficult and only avoided by implementation of all available demand and supply side options.

- **Further examination of the link between water resources management planning and drought planning, including the use of ‘headroom’.** The workshops highlighted the fact that some water companies used ‘headroom’ for managing drought. This indicates a need for clarification of the difference between ‘headroom’ and useable freeboard for drought, and raises the question whether drought margins should be built into water resources management plans. Further research into the value of making the systems more resilient to severe drought including cost–benefit analysis is needed. This includes a need for further exploration of the links between deployable output, levels of service and frequency of restrictions. Investigations are needed into the actual frequency of use of demand restrictions taking account of the target frequency and published levels of service.
- **Testing of the drought management planning and management system for groundwater dominated water resource zones**. Drought exercises similar to those undertaken for surface water reservoirs in this project could also be carried out for groundwater sources. Technically this would be a more difficult exercise requiring more advanced modelling. There is a clear need for further work on the impacts of long droughts on groundwater resources in England and Wales.
- **Further research on the impacts of climate change on autumn flows.** During the workshops it became clear that both water companies were highly dependent on autumn flows for reservoir recovery. This suggests that forecasting autumn rain and flow could be more important than at any other time of year and that particular attention should be given to the impact of climate change on autumn flows.
- **Research on practical use of drought indices for monitoring drought development.** For contemporary drought monitoring, rainfall and runoff deficiencies are widely used. There is considerable potential for the application of a version of the Drought Severity Index within drought monitoring, but more work is required to develop the index further; in particular, the sensitivity to termination criteria should be explored and suitable criteria should be developed for a range of water supply systems.

6.3 Other recommendations

A need for improved hydrological reporting and more frequent publication during severe droughts by the Environment Agency was identified at the workshops. Improvements to drought reporting are currently being implemented by the Environment Agency, but it is not clear whether there is a consistent and accurate approach to hydrological reporting and forecasting across the UK. The Environment Agency operates a large telemetry system including rainfall, river flow and groundwater level gauges that could be used to provide weekly reviews during drought periods.

References and Bibliography

Alexander L V and Jones P D, 2001 Updated precipitation series for the United Kingdom. *Atmospheric Science Letters*, 1, 142-150.

Anglian Water, 2008 *Drought Plan*. Huntingdon: Anglian Water. Available from: http://www.anglianwater.co.uk/environment/water-resources/drought-plan/ [Accessed 11 December 2009].

Anglian Water Services and Mott Macdonald, 1997 Surface water yield estimates. Peterborough: Anglian Water Services.

Bayliss A, Norris J and Marsh T J, 2004 The Wendover Springs record: an insight into the past and a benchmark for the future. *Weather*, 59, 267-271.

BHS, 2009 *Chronology of Hydrological Events* [online]. London: British Hydrological Society. Available from: http://www.dundee.ac.uk/geography/cbhe/ [Accessed 11 December 2009].

Bloomfield J P, Gaus I and Wade S D, 2003 A method for investigating the potential impacts of climate change scenarios on annual minimum groundwater levels. *Water and Environmental Journal,* 17(2), 86-91.

Briffa K R, van der Schrier G and Jones P D, 2009 Wet and dry summers since 1750: evidence of increasing drought. *International Journal of Climatology*, 29(13), 1894-1905.

Bryant S J, Arnell N W and Law F M, 1994 The 1988–92 drought in its historical perspective. In Proceedings of CIWEM Annual Symposium on the Management of Scarce Water Resources (Brighton, 1992). London: Chartered Instittition of Water and Environmental Management [Water and Environment Journal, 8(1), 39-51, 1994].

CEC, 2007 *Addressing the challenge of water scarcity and droughts in the European Union. Communication from the Commission to the European Parliament and the Council.* COM(2007) 414 final. Brussels: Commission of the European Communities. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0414:FIN:EN:PDF [Accessed 11 December 2009].

CEH and BGS, 2003 *Hydrological data United Kingdom. Hydrometric Register and Statistics 1996-2000.* Wallingford: Centre for Ecology & Hydrology. Available from: http://nora.nerc.ac.uk/6950/ [Accessed 11 December 2009].

CEH, 2009 Water Watch [online]. National Hydrological Monitoring Programme. Wallingford: Centre for Ecology & Hydrology. Available from: http://www.ceh.ac.uk/data/nrfa/water_watch.html [Accessed 11 December 2009].

Clayton H J, Morris S E, McIntyre N R and Greaves M, 2008 The hydrological impact of low flow alleviation measures. *Water Management*, 161, 171-180.

Codling, I.D. and Mistry, R.K, 2006 Environmental Monitoring Plan for Drought Plan, WRc Report No.: UC7101

Cole G and Marsh T J, 2006 Major droughts in England and Wales from 1800 and evidence of impact. SC040068/SR1. Bristol: Environment Agency

Davies A W, 1978 Pollution problems arising from the 1975–1976 drought. *Proceedings of the Royal Society of London A*, 363, 97-107.

Defra, 2005 Drought orders and drought permits. Information from the Department for Environment, Food and Rural Affairs, Welsh Assembly Government and the Environment Agency. London: Defra. Available from: http://www.defra.gov.uk/environment/quality/water/resources/drought/index.htm [Accessed 11 December 2009].

Doornkamp J C, Gregory K J and Burn A S 1980 Editors *Atlas of Drought in Great Britain, 1975–1976*. Southampton: Institute of British Geographers, Ordnance Survey.

Environment Agency, 2001 Water resources for the future. A strategy for England and Wales, ISBN 185705508X

Environment Agency, 2003 *Thames Region Drought Plan.* Bristol: Environment Agency.

Environment Agency, 2005 Water Company Drought Plan Guideline 2005 Version 2.0. Bristol: Environment Agency. Available from: http://www.environment-agency.gov.uk/business/sectors/39697.aspx [Accessed 11 December 2009].

Environment Agency, 2006a *Drought prospects 2006*. Bristol: Environment Agency.

Environment Agency, 2006b *Drought prospects 2006 – spring update*. Bristol: Environment Agency.

Environment Agency, 2006c *Drought prospects 2006 – August update*. Bristol: Environment Agency.

Environment Agency, 2007 Environment Agency Draft Drought Plans Consultation Response Document for England and Wales, March 2007

Environment Agency, 2008 *Hydrological summary of the 2004-2006 drought*. Bristol: Environment Agency.

Fleig A, 2004 *Hydrological drought – a comparative study using daily discharge series from around the world*. PhD thesis, Albert-Ludwigs Universität, Freiburg, Germany.

Fleig A K, Tallaksen L M, Hisdal H and Demuth S, 2006 A global evaluation of streamflow drought characteristics. *Hydrology and Earth System Sciences*, 10, 535-552.

Fowler H J and Kilsby C G, 2002 A weather-type approach to analysing water resource drought in the Yorkshire region from 1881 to 1998. *Journal of Hydrology*, 262, 177-192.

Hisdal H, Tallaksen L M, Clausen B, Peters E and Gustard A, 2004 *Hydrological drought characteristics*. In Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, Volume 48 (ed. L M Tallaksen and H A J van Lanen), pp. 139-198. Amsterdam: Elsevier.

HR Wallingford, 2007 *The 'long drought' in south east England 1890 to 1909: evidence and reasons for inclusion in Southern Water's Draft Water Resources Plan*. Technical Note 01. Wallingford: HR Wallingford.

Jones P D, 1980 A homogeneous rainfall record for the Cirencester region. *Meteorological Magazine*, 109, 249-258.

Jones P D, 1981 A survey of rainfall recording in two regions of the Northern Pennines. *Meteorological Magazine*, 110, 239-252.

Jones P D, 1983 Further composite rainfall records for the United Kingdom. *Meteorological Magazine*, 112, 19-27.

Jones P D, 1984 River flow reconstruction from rainfall data. *Journal of Climatology*, 4, 171-186.

Jones P D and Conway P D, 1997 Precipitation in the British Isles: An analysis of area-average data up to 1995. *International Journal of Climatology*, 17, 427-438.

Jones P D and Lister D, 1997 *Extended flow records at key locations in England and Wales (Phase 2).* R&D Technical Report W25. Bristol: Environment Agency.

Jones P D and Lister D H, 1998 River flow reconstructions and their analysis on 15 catchments over England and Wales. *International Journal of Climatology*, 18, 999-1013.

Jones P D, Ogilvie A E J and Wigley T M L, 1984 *River flow data for the United Kingdom: reconstructed data back to 1844 and historical data back to 1556.* Climatic Research Unit Research Publication, CRURP 8. Norwich: Climatic Research Unit, University of East Anglia.

Jones P D, Conway D and Briffa K R, 1997 *Precipitation variability and drought*. In Climates of the British Isles: Present, Past and Future (ed. M Hulme and E Barrow), pp. 197-219. London: Routledge.

Jones P D, Lister D H and Kostopoulou E, 2003 *Reconstructed river flow series from 1860s to present. Updating previously reconstructed series to 2002.* Science Report SC040052/SR. Bristol: Environment Agency.

Jones P D, Leadbetter A, Osborn T J and Bloomfield J P, 2006a *The impact of climate change on severe droughts. River-flow reconstructions and implied groundwater levels.* Science Report SC040068/SR2. Bristol: Environment Agency.

Jones P D, Lister D H, Wilby R L and Kostopoulou E, 2006b Extended river flow reconstructions for England and Wales 1865-2002. *International Journal of Climatology*, 26, 219-231.

Kilsby C G, Jones P D, Burton A, Ford A C, Fowler H J, Harpham C, James P, Smith A and Wilby R L, 2007 A daily weather generator for use in climate change studies. *Environmental Modelling and Software*, 22, 1705-1719.

Lloyd Hughes B and Saunders M A, 2002 A drought climatology for Europe. *International Journal of Climatology*, 22, 1571-1592.

Lloyd Hughes B, Hannaford J, Parry S, Keef C and Prudhomme C, 2010 *The spatial coherence of European droughts – UK and European drought catalogues*. Report SC070079/R1. Bristol: Environment Agency.

Lopez A, Fung F, New M, Watts G, Weston A and Wilby R, 2008 *From climate model ensembles to climate change impacts: a case study of water resources management in the south west of England.* In Proceedings of international conference Climate Change Impacts and Adaptation: Dangerous Rates of Change (Exeter, 2008). Available from: http://www.exeter.ac.uk/climatechange/conference/documents/B2Ana_Lopez.pdf [Accessed 11 December 2009].

Manley G, 1974 Central England temperatures: monthly means 1659 to 1973. *Quarterly Journal of the Royal Meteorological Society*, 100, 389-405.

Marsh T J and Hannaford J, 2008 Editors *UK Hydrometric Register*. Hydrological Data UK series. Wallingford: Centre for Ecology & Hydrology. Available from: http://www.ceh.ac.uk/products/publications/UKHydrometricRegister.html [Accessed 11 December 2009].

Marsh T J, Monkhouse R A, Arnell N W, Lees M L and Reynard N S, 1994 *The 1988–1992 drought.* Hydrological Data UK Series. Wallingford: Institute of Hydrology and British Geological Survey.

Marsh T, Cole G and Wilby R, 2007a Major droughts in England and Wales, 1800–2006. *Weather*, 62(4), 87-93.

Marsh T J, Booker D and Fry M, 2007b *The 2004–2006 drought.* Hydrological Data UK series. Wallingford: Centre for Ecology & Hydrology. Available from: http://www.nwl.ac.uk/ih/nrfa/water_watch/dr2004_06/index.html [Accessed 11 December 2009].

Mawdsley J A, Petts G E and Walker S, 1994 *Assessment of drought severity*. Occasional Paper No. 3. London: British Hydrological Society.

McKee T B, Doesken N J and Kliest J, 1993 *The relationship of drought frequency and duration to time scales*. In Proceedings of the 8th Conference on Applied Climatology (Anaheim, CA, 1993). Boston, MA: American Meteorological Society.

Moore R J., Bell V A, Cole S J and Jones D A, 2007 *Rainfall-runoff and other modelling for ungauged/low-benefit locations: operational guidelines*. Science Report SC030227/SR2. Bristol: Environment Agency.

Parker D E, Legg T P and Folland C K, 1992 A new daily Central England temperature series, *International Journal of* Climatology, 12, 317-342.

Perry M, 2006 *A spatial analysis of trends in the UK climate since 1914 using gridded datasets*. National Climate Information Centre, Climate Memorandum No. 21. Exeter: Met Office. Available from: http://www.metoffice.gov.uk/climate/uk/about/UK_climate_trends.pdf [Accessed 11 December 2009].

Perry M and Hollis D, 2005a The development of a new set of long-term climate averages for the UK, *International Journal of* Climatology, 25, 1023-1039.

Perry M and Hollis D, 2005b The generation of monthly gridded datasets for a range of climatic variables over the UK, *International Journal of* Climatology, 25, 1041-1054.

Phillips I D and McGregor G R, 1998 The utility of a drought index for assessing the drought hazard in Devon and Cornwall, South West England. *Meteorological Applications*, 5, 359-372.

South West Water, 2007 *Drought Plan*. Exeter: South West Water. Available from: http://www.southwestwater.co.uk/index.cfm?articleid=659 [Accessed 11 December 2009].

Strahan A, MacKenzie N F, Mill H R and Owens J S, 1916 *The investigation of rivers: final report*. London: Royal Geographical Society.

Stahl K and Demuth S, 1999 Linking streamflow drought to the occurrence of atmospheric circulation patterns. *Hydrological Sciences Journal*, 44, 467-482.

Tabony R C, 1980 *A set of homogeneous European rainfall series.* Met Office 13 Branch Memorandum No. 104. Bracknell: Meteorological Office.

Tallaksen L M, Madsen H and Clausen B, 1997 On the definition and modelling of streamflow drought duration and deficit volume. *Hydrological Sciences Journal*, 42(1), 15-34.

Thames Water, 2006 *Water Resources Act 1991. Application for an ordinary drought order – London. Statement of reasons.* Reading: Thames Water Utilities Ltd.

Toth F L, 1998 Policy exercises: procedures and implementation, *Simulation and Gaming*, 19(3), 256-276.

UKWIR, 1997 *Effects of climate change on river flows and groundwater recharge: guidelines for resource assessment*. UKWIR Report 97/CL/04/1. London: UK Water Industry Research.

Van der Schrier G, Briffa K R, Jones P D and Osborn T J, 2006 Summer moisture variability across Europe. *Journal of Climate*, 19, 2818-2834.

Vidal J P and Wade S D, 2008 Multimodel projections of catchment-scale precipitation regime, *Journal of Hydrology*, 353 (1-2), 143-158.

Vogel R M and Stedinger J R, 1987 Generalised storage-reliability-yield relationships. *Journal of Hydrology*, 89, 303-327.

Wade S D and Vidal J P, 2007 The effects of climate change on river flows and groundwater recharge. Synthesis Report. UKWIR/Environment Agency R&D.

Wade S, Jones P D and Osborn T J, 2006 *The impact of climate change on severe droughts: implications for decision making*. Science Report SC040068/SR3. Bristol: Environment Agency.

Waterwise, 2006 *Garden watering restrictions. A report to Defra reviewing international models of external water use restrictions*. London: Waterwise. Available from: http://www.defra.gov.uk/environment/quality/water/resources/research/index.htm [Accessed 11 December 2009].

Wigley T M L, Lough J M and Jones P D, 1984: Spatial patterns of precipitation in England and Wales and a revised, homogeneous England and Wales precipitation series. *Journal of Climatology*, 4, 1-25.

Wilhite D A and Glantz M H, 1985 Understanding the drought phenomenon: the role of definitions. *Water International*, 10, 111-120.

Wright C E, 1978 *Synthesis of riverflows from weather data*. Technical Note No. 26. Reading: Central Water Planning Unit.

Wright C E and Jones P D, 1982 *Long period weather records, drought and water resources*. In Optimal Allocation of Water Resources, IAHS Publication No. 135 9ed. M J Lowing), 89-100. Wallingford: International Association of Hydrological Sciences.

Zaidman M D, Rees H G and Young A R, 2002 Spatio-temporal development of streamflow droughts in northwest Europe. *Hydrology and Earth System Sciences*, 6, 733-751.

List of Abbreviations

ADO	average deployable output
ALF	alleviation of low flow
AMP	Asset Management Plan [a review of water prices associated with an agreed infrastructure programme]
AWS	Anglian Water Services
BFI	Base Flow Index
BGS	British Geological Survey
CAMS	Catchment Abstraction Management Strategy
CCW	Countryside Council for Wales
CCWater	Consumer Council for Water
CEH	Centre for Ecology & Hydrology
CET	Central England temperature
CRU	Climatic Research Unit, School of Environmental Sciences, University of East Anglia
Defra	Department for Environment, Food and Rural Affairs
DO	deployable output
DOC	dissolved oxygen content
DSI	Drought Severity Index
DWI	Drinking Water Inspectorate
EIA	Environmental Impact Assessment
EU	European Union
GET	Generalised Environmental Trigger
GS	gauging station
LoS	level of service
Ml	Mega litre
MRF	minimum residual flow
NR	no restrictions
NWA	National Water Archive
NWP	numerical weather prediction
Ofwat	Office of Water Services
OPA	Overall Performance Assessment
PDSI	Palmer Drought Severity Index
PET	potential evapotranspiration

pf	preferential flow
PS	pumping station
RBMP	River Basin Management Plan
RDI	Regional Deficiency Index
RGS	remote ground station
RSPI	Regional Standardised Precipitation Index
SPA	sequent peak algorithm
SPI	Standardised Precipitation Index
SSA	Strategic Supply Area
WAG	Welsh Assembly Government
WB	water basin
WFD	Water Framework Directive
WHD	worst historic drought
WRMP	Water Resources Management Plan
WRZ	Water Resource Zone
WTW	water treatment works

Appendix A Literature summaries

Author/Title	*Drought Plan*, Anglian Water, 2008. http://www.anglianwater.co.uk/environment/water-resources/drought-plan/
Scope	This document details Anglian Water's latest drought plan in accordance with the Water Act 2003 and follows on from its last non-statutory plan submitted in 2003 to the Environment Agency. It is consistent with the company's water resources management plan which assessed the supply–demand balance.
Summary	**Drought management to date.** Water use restrictions were last imposed by Anglian Water in 1991 to meet environmental concerns, but they were not needed to secure water supply. The water supply system is robust to short periods of low rainfall (due to their characteristics), e.g. the water storage reservoirs are resilient to these conditions since they have long retention periods. It is continuous periods of extremely dry weather that need to be prepared for. Winter rainfall was below average in 2004–2005, prompting the situation to be monitored closely. A dry winter followed in 2005–2006, which resulted in further actions including water efficiency campaigns. This prevented the need for restrictions or drought orders. Relevant work that Anglian Water has carried out since its last drought plan includes the Water Resources Plan 2004, its draft Water Resources Management Plan (WRMP) and a National Environment Plan (NEP) to address environmental impacts of abstractions, looking specifically at the Ouse and Nene Washes. It also has a Water Resources Environment Programme (WREP). **Water resources planning.** The WRMP, which was submitted in 2004, looked at deployable outputs as well as the supply–demand balance. The availability of headroom, which covers uncertainty in water resources calculations, is assessed in the Security of Supply Index (SOSI) every year. Anglian Water has considered the potential impacts of climate change through the use of the UKCIP02 scenarios and feels they could be more severe than previously considered. Drought management supply and demand options are based on water resource zones, though a local authority basis will be use to implement demand management options. **Drought scenarios.** Anglian Water used a number of different historic droughts to determine how reservoir yields would be affected and consequently how drought management would be affected. The response varied with the location, type and capacity of the reservoir. Drought management needs to be flexible due to the variable nature of rainfall and the large area covered. **Drought actions.** These will be implemented according to the drought status published by the Environment Agency and the occurrence of drought conditions through the use of drought triggers

	based on an assessment of yields. Anglian Water's communications strategy is also implemented according to this. The company has provisionally prepared three cases for drought orders in its plan. **Managing supply and demand.** It is necessary to combine resource development with demand management strategies. Levels of service during drought conditions are used to measure this supply–demand balance against forecast demand. Anglian Water's policies on water supply were developed and tested following severe droughts in the 1990s. Demand-side management measures are important, with an increase in communication to the public/stakeholders corresponding to drought intensity. Such measures prevent the need to apply for drought orders. Anglian Water applied for drought orders to refill Grafham and Pitsford reservoirs during the winters in 1976 and 1997. However, the first application was not needed and the second was withdrawn. Anglian Water identified that new resources may need to be developed towards the middle and end of the 25-year planning period (as in the WRMP) because climate change, water quality deterioration and demand increases as a result of population changes and growth could decrease deployable outputs. A supply–demand balance model was used to project this. Demand-side management has so far proved effective, stabilising the growth in demand for water since the 1990s. Other implemented methods include the installation of water meters and leakage control. Tourism means that coastal areas may experience a peak demand according to the season and the weather. **Groundwater.** Around half of Anglian Water's customers are supplied with water from groundwater resources. This is abstracted from a variety of over 400 boreholes. These are monitored continuously with pumping water levels under review due to low groundwater levels (vital for water resources management). Boreholes can be assessed for their susceptibility to drought through an understanding of aquifer characteristics, including local conditions and groundwater flow. These will change in response to low recharge rates. A management plan is in place to respond to decreasing borehole levels during drought. **Environmental impacts.** Both Anglian Water and the Environment Agency have investigated the impacts of abstractions on the environment including on Natura 2000 sites. The Environmental Monitoring Plan relates to the drought orders proposed in the plan which would reduce residual flows. Anglian Water has also considered mitigation strategies including environmental support pumping.
Key points	
Data issues	
Comments	

Author/Title	*Drought orders and drought permits. Information from the Department for Environment, Food and Rural Affairs, Welsh Assembly Government and the Environment Agency*, Defra, 2005. http://www.defra.gov.uk/environment/quality/water/resources/drought/index.htm
Scope	This document provides information on drought permits and drought orders and details the process for obtaining them.
Summary	Drought orders and permits can be granted under the Water Resources Act 1991, amended by the Environment Act 1995 and the Water Act 2003. Three types are available – drought permits, ordinary drought orders and emergency drought orders. Drought permits are granted by the Environment Agency, while ordinary drought orders and emergency drought orders are authorised in England by the Secretary of State and in Wales the National Assembly for Wales. Drought orders and permits are only granted in exceptional circumstances when water supplies are in severe shortage due to a lack of rainfall. The water company will need to have made an effort to implement demand-side management measures in accordance with the associated impacts on the environment (Environment Agency 2005). Such measures include public campaigns to reduce the use of water, hosepipe bans and leakage control. Water companies have powers to implement hosepipe bans if they need to without requiring a drought order. The Drought Direction 1991 specifies the different non-essential uses that can only be restricted when a drought order is granted. The Environment Agency will take other water users into account when granting drought permits or supporting drought orders. However, it does appreciate that water companies may need to apply for orders and permits to enable them to meet supply requirements during droughts. Potential drought permits must be considered in a drought plan otherwise it is unlikely they will be granted. Drought orders must also be considered in the plan otherwise the application will not usually be supported by the Environment Agency. Consideration should be given to location, mitigation of impacts and when measures should be implemented to ensure that minimum damage will occur to the environment. For example, winter drought permits are normally preferred by the Environment Agency since they can help to monitor and replenish resources as well as reducing the likelihood of the need for drought orders or permits during the summer. There are a number of steps involved in applying for a drought order or drought permit which requires a lot of preparation. This includes submission of an environmental report along with the application.
Key points	
Data issues	
Comments	

Author/Title	*Water Company Drought Plan Guideline 2005 Version 2.0,* Environment Agency, 2005 http://www.environment-agency.gov.uk/business/sectors/39697.aspx
Scope	This document provides guidance on the content and structure of the statutory 2006–2007 drought plans to be submitted by water companies. The guidelines are a revision of the Environment Agency's drought plan guidelines issued in 2002.
Summary	The Water Act 2003 introduced new legislation into the Water Industry Act 1991 under which drought plans must be prepared and submitted. Water companies had previously submitted drought plans to the Environment Agency; the process is now statutory and the plans must be submitted to the Secretary of State/Welsh Assembly Government (WAG) Water companies have different drought plans to the Environment Agency since their role in drought management is different. Drought plans detail how a water company will meet water supply requirements during a drought without too much reliance on drought permits or drought orders. This will also avoid any detriment to the environment where possible. The most important issues that must be addressed in the drought plan are: • what demand-side management measures might need to be implemented by the water company; • what supply-side measures might need to be implemented by the water company; • how the effects of the drought and management measures implemented will be monitored. There are a number of steps in the drought plan process, including consultation before the plan is prepared with a variety of parties including the Secretary of State/WAG, Environment Agency, Ofwat and licensed water suppliers. Some of the main requirements are as follows: • A management plan should be included detailing each stage and when these should be implemented. This includes details of the possible actions to be taken during the drought and as it recedes. These correspond to the severity of the drought, e.g. what stage of drought management should be implemented once a trigger is reached. • It is important that the plan considers a number of different scenarios. These include different ranges of dry summers and winters as well as multi-season droughts. This will improve the plan's resilience to a number of possible drought situations and therefore improve management planning. The plan must state the reasons for choosing these scenarios. • The plan needs to be consistent with the company's water resources management plan (WRMP) in terms of deployable outputs calculated and levels of service used. • The plan should set out how the drought will be monitored.

	• The plan should consider any potential impacts on the environment of the area. The water company will need to monitor the environment, highlighting any designated areas of ecological importance such as any sites designated under the Conservation (Natural Habitats, &c.) Regulations 1994. Environmental factors that could be affected by any drought measures described in the plan should be detailed at these sites individually to determine if there are any environmental implications. This could be achieved through the use of the Environment Agency's monitoring data records as well as consultation with Natural England or CCW. In cases where there could potentially be impacts on water or the environment as a result of its drought plan then mitigation measures should be in place. • The plan should explain how the company will use its communication strategy to provide information to customers. • Actions to be taken following the drought should be highlighted. There should be a commitment to review and, if necessary, update the plan. Potential sites for drought orders and drought permits should also be considered, otherwise it is unlikely they will be granted or supported by the Environment Agency.
Key points	The drought plan ensures the security of supply of water throughout a drought. Every water company should follow these guidelines when preparing their drought plan.
Data issues	
Comments	

Author/Title	*Drought prospects 2006,* Environment Agency, February 2006
Scope	This report provided: • an overview of the water resources situation in England and Wales in February 2006; • recommendations for actions by water companies and other abstractors.
Summary	The state of water resources was described as ‘scarce’ in February 2006 and, even with average rainfall for the rest of the winter, water supply management was assessed to be difficult in much of south-east England. Mid-Kent was identified as the area of highest risk from drought in the summer of 2006 though the situation was quite severe in all of south-east England. Met Office forecasts indicated warmer than average weather – drier than average in the north but equal probabilities of drier weather in the south. The forecasts are generally associated with high uncertainty and it was therefore necessary to consider the possibility of continued dry conditions. Based on forecasts of the consequences of different rainfall forecasts (60, 80 and 100 per cent of average), a number of recommendations for the water companies were put forward. These included: • Maintain and publicise current hosepipe bans. In areas without hosepipe bans, introduce them from early April at the latest. • Apply for non-essential use bans to restrict uses of water such as window washing and building washing before applying for drought permits or orders to take more water from rivers and groundwater. • Make sure that customers understand the severity of this drought, with clear publicity campaigns. • Provide clear information and advice to customers on how they can save water in the home. This could include publicity campaigns either individually or with other water companies. • Increase leakage control activity to make sure that leaks are found and fixed as quickly as possible, reducing the waste of water. • Work with large industrial water users to look for significant short-term savings in water use. • Follow your drought plans and make sure steps to save water are taken in good time. • Prepare to make drought permit and drought order applications in line with your drought plans as soon as it becomes clear that they will be necessary. • Make sure that drought management responsibilities are assigned clearly, so that there is no unnecessary delay in decision-making.

	• Work together to make best use of available resources across south-east England, using transfer schemes to move water to places where it is needed most. Similarly the Environment Agency outlined its actions: • Provide regular progress reports for Ministers. • Monitor water companies' activities to make sure that they take all possible steps to manage drought. • Increase monitoring of rainfall, river flows, groundwater levels and the environment. • Continue weekly reporting on drought on its website. • Update its computer modelling regularly to provide the best possible information about the impact of drought. • Provide clear information for the public on how they can report environmental problems and how they can help to save water. • Provide the best information possible on the impact on agriculture, including possible restrictions on spray irrigation. • Take steps to protect the environment from drought including: – where in place, use its river support schemes to maintain flows and protect wildlife; – restricting spray irrigation where this will provide significant benefit to the environment; – apply for drought orders where these will mitigate the impact of drought on the natural environment. • Report publicly on the impact of the drought on the environment and wildlife. • Apply for drought orders on behalf of water companies where it believes that inaction is putting water supplies at unacceptable risk. The report encourages the water companies to act quickly to make the best use of available water. Any delay could exacerbate the situation. It is also stressed that, while the water companies make their own decisions about measures, they must defend their approach to customers/regulators if advice from the Environment Agency is ignored.
Key points	Environment Agency recommendations should be followed by the water companies.
Data issues	
Comments	It is not clear what the consequences might be if the Environment Agency advice is not taken (apart from that associated with application for drought orders).

Author/Title	*Drought prospects 2006 – spring update*, Environment Agency, May 2006.
Scope	The purpose of the report was to: • refine the Environment Agency's view of prospects for the water resources situation in England and Wales in the summer of 2006; • evaluate actions by water companies; • provide recommendations for further actions by water companies and other abstractors.
Summary	The overall assessment of the risk of a severe drought developing did not change from February 2006 to May 2006. There was a real but small risk of standpipes in parts of south-east of England. London's resources were at particular risk due to failure of the intake tunnel for the Queen Mother reservoir reducing the capacity by about 10 per cent. Essex and Sussex were also assessed to be at risk, although because reservoirs were close to full, a hosepipe ban had not been introduced. Drought permits were used to increase reservoir levels in Bewl (Southern Water). Actions taken by the water companies from February to May (based on recommendation from the Environment Agency) included hosepipe bans for 13 million people. Three water companies applied for drought orders for restrictions of non-essential use to the Secretary of State. Water companies had worked closely with the Environment Agency in publicity campaigns to raise awareness of the drought and encourage the saving of water. The hosepipe ban had resulted in negative reactions from gardeners blaming mismanagement of water resources by the water companies. The amount of water saved by the ban had been much less than water leakage from pipes. A new drought permit was issued to Sutton and East Surrey Water to allow pumping into Bough Beech reservoir until the end of May. Two drought permits already in force (Bewl and Hardham) had been extended. A table in the report outlined actions taken by each company based on recommendations from February. The Environment Agency recommended further actions: • Essex and Suffolk Water should apply for a hosepipe ban in May. • Portsmouth Water should monitor the situation closely. • Other water companies (including Thames Water) should prepare to apply for non-essential use bans. • Further work on leakage control was required in addition to increased levels of investment. The Environment Agency recommended investment above the economic level of leakage. • Further drought permit applications were anticipated although

	wetter weather reduced the immediate need. More general recommendations were also put forward, very similar to the original from February. The Environment Agency actions were also largely the same. The report encouraged the water companies to act quickly to make the best use of available water as any delay could exacerbate the situation. Concerns of a third dry winter were mentioned. Dedicated drought teams were set up to manage the impact of drought and to monitor the actions of the water companies.
Key points	Provides an assessment of the actions taken by the water companies and further recommendations.
Data issues	
Comments	

Author/Title	*Drought prospects 2006 – August update*, Environment Agency August 2006
Scope	The purpose of the report was to: - refine the Environment Agency's view of prospects for the water resources situation in England and Wales at the end of the summer of 2006; - evaluate actions by water companies; - provide recommendations for further actions by water companies and other abstractors.
Summary	The drought continued through the summer with severe implications for the environment. Ponds and rivers dried up and several incidents of fish deaths and algal blooms occurred. To manage the drought the Environment Agency introduced formal restrictions on 600 spray irrigation licences in excellent co-operation with the farmers. The water supply situation was reasonably good, with reservoir levels close to normal. The improved situation was attributed to the success of water companies' actions: - Hosepipe bans, non-essential use bans and appeals to save water reduced demand by 5–15 per cent. - All companies increased their leakage control activities and many were below planned targets for the year. - Additional old boreholes had been brought into use. All water companies reported that they were able to manage groundwater supplies for the following months but were concerned about the prospects for the following summer if there was another dry winter. The Environment Agency recommended further actions by the water companies: - Continue to ask people to save water this summer and autumn. - Maintain restrictions on water use until resources have recovered fully. - Explain to customers that the drought is not over yet. - Keep under active review the need to implement additional restrictions on water use allowed by drought orders. If the rest of the summer and autumn are dry, these may still prove necessary in some places. - Make sure that leakage is kept under control throughout the autumn and the winter. - Review the need for drought permits to allow additional abstraction of water to fill reservoirs this winter and prepare

	applications in good time.
Key points	Actions by the water companies were assessed as successful and crucial to managing the impact on the drought on demand/supplies. Demand was reduced even where there were no hosepipe bans because many people believed that restrictions applied across the region.
Data issues	
Comments	As the drought ended after August there is no information on whether people continued to save water in the autumn or whether any of the recommended actions were followed after August.

Author/Title	*Hydrological summary of the 2004–2006 drought*, Environment Agency, 2008
Scope	The report provided a summary of the 2004–2006 drought and how it affected the Thames Region of the Environment Agency.
Summary	The Thames Region has an annual average rainfall of 690 mm, making it one of the driest Environment Agency regions. A below average rainfall for 19 months between 2004–2006 was experienced, causing a drought period which covered two dry winters as well as a dry summer. The aquifers in the region depend on winter rainfall for their recharge, meaning that groundwater resources were particularly affected by the drought. Recharge of major aquifers in the Thames Region was reduced, ranging from one third of normal recharge of Chalk aquifers in the Chilterns to one half of normal recharge of the Oolites in the northern part of the region. Much of this region was determined as having ‘exceptionally low’ recharge from an analysis by the Environment Agency. By summer 2006, groundwater levels were either ‘noticeably low’ or ‘exceptionally low’ according to the Environment Agency’s classification. This in turn impacted the spring-fed rivers in the region. There are a number of groundwater-dependent streams and rivers in the Thames catchment including the River Pang and the River Lambourn. These chalk-fed rivers are highly variable in terms of their source location and are affected by drought conditions. Water is sometimes abstracted from rivers and groundwater to make up for this; however, the needs of the environment must be considered and strategies are in place to mitigate any potential adverse impacts. During the drought, river flows varied according to their dependence on groundwater flows and the geology type. There were a number of visible effects on the environment during the 2004–2006 drought. These included the presence of algal blooms, ponds drying out as well as noticeable impacts on fish due to low flows. Drought management was under close scrutiny, with a number of associated stakeholders involved. Hosepipe bans were imposed, including for the first time in London since 1990. Drought orders were applied for by Thames Water and Southern and East Surrey Water; the former application was withdrawn while the latter was effective over the summer of 2006 for almost six months. The return to normal river flows and groundwater levels was delayed as the high rainfall in the winter of 2006 replenished deficits in effective rainfall. There were questions as to what the situation would have been like if there was a third successive dry winter.
Key points	The impacts of a drought on available water resources and the environment were evident.
Data issues	
Comments	

Author/Title	*Drought Plan*, South West Water, 2007 http://www.southwestwater.co.uk/index.cfm?articleid=659
Scope	This document details South West Water's latest drought plan in accordance with the Water Act 2003. It is consistent with the company's Water Resources Management Plan (WRMP).
Summary	The drought plan takes into account a wide variety of scenarios in accordance with the guidelines produced by the Environment Agency. These scenarios consider levels of demand, single and multi-season droughts as well as anticipated climate change. Wimbleball, Colliford and Roadford are the three strategic supply areas (SSAs) used by South West Water to manage its water resources and the drought plan is based on these. This accounts for the operational constraints in the supply system. **Drought management.** The drought management curves used were derived for each of the SSAs, dividing local and strategic reservoirs into different zones. The curves relate to the levels of service used by South West Water, which detail the possible frequency of drought management measures. The company's strategy in the management of its water resources is to first use local sources of water before strategic reservoirs. Local sources may be augmented by appropriate management strategies if a drought should occur at any of these. But if drought conditions occur at one of the strategic sources, then South West Water may need to apply for a drought order. The time taken to implement each of the measures is also considered, e.g. drought orders take much longer to apply for than hosepipe bans. Both demand-side and supply-side drought management options are detailed in the drought plan: *Demand-side measures*: • Publicity, water efficiency campaigns, water conservation measures • Leakage control and pressure management • Hosepipe bans • Bans on the non-essential use of water *Supply-side measures:* • Emergency capital works • Distribution zone management – demand is transferred from sources that may be stressed to those which have a more abundant supply (South West Water has made extensive use of this option in the past.) • Emergency abstractions • Reduced compensation flows

	• Reduced prescribed flows. **Environmental impacts.** Surveillance and monitoring programmes will allow South West Water to identify the potential impacts on the environment as a result of the implementation of supply-side measures that may exceed the impacts of the drought itself. Mitigation measures can be implemented either before the drought order is in place or in response to any observed impacts that may be detrimental to the environment. **Groundwater.** Regular monitoring of three sites is carried out to monitor the state of groundwater resources and to allow comparison with long-term statistics. Other indicators are considered to determine low groundwater levels as it hard to predict these. **Communications plan.** This uses a phased approach which would be implemented in early spring should a drought look likely, followed by further actions later in the year if it does occur. This will be revised during the drought. Monitoring information is provided in the weekly water situation report (WSR) sent to a number of relevant organisations.
Key points	
Data issues	
Comments	

Author/Title	*Water Resources Act 1991. Application for an ordinary drought order – London. Statement of reasons*, Thames Water Utilities Ltd, 2006
Scope	During the 2004–2006 drought, Thames Water submitted an application for an ordinary drought order covering the London water resources area of supply. The details are given in this document.
Summary	Thames Water stated that it needed to apply for the drought order to avoid the possible need for an emergency drought order in the event of a third dry winter. It claimed this would be unacceptable in a major city such as London due to adverse effects on the environment, society and the economy. The London water resource zone obtains 80 per cent of its water resources from the lower Thames and lower Lee riverflows. Groundwater levels are also important for water supply in the Thames catchment and, due to the dry winters experienced during the drought, reservoir storage had declined quickly. Groundwater contributes to the flows of the rivers, so these storage levels determine the availability of water resources to London. Lower levels lead to low river baseflows in spring, summer and autumn which would threaten the security of supply to London. If surface water levels become low, then abstractions cannot meet demand and water is then dependent on reservoir sources. With more water being used from the reservoir, water levels decline quickly and this can lead to the use of groundwater reservoirs such as the Chalk aquifer of the Berkshire Downs. Hosepipe bans were already in place when the application for the drought order was submitted, as well as a media campaign to promote water efficiency. Granting a drought order would be the next level of demand restrictions needed to be implemented according to Thames Water. Moreover in its *Drought Prospects Update*, the Environment Agency recommended that Thames Water make this drought order application. Thames Water used its Water Resources Management System model to predict river flow levels. Hydrographs of a number of past droughts were plotted against those for 2006 with 50 per cent average rainfall as the scenario. Riverflows were predicted as being only slightly higher than those in the summer of 1976 for the Lower Thames if there was a third dry winter. Thames Water also predicted that by October that year reservoir levels could drop as low as 30 per cent, which would prompt the need for drastic management strategies.
Key points	
Data issues	
Comments	

Author/Title	*Garden watering restrictions. A report to Defra reviewing international models of external water use restrictions*, Waterwise, November 2006 http://www.defra.gov.uk/environment/quality/water/resources/research/index.htm
Scope	The report clarifies the objectives of introducing hosepipe bans and suggests amendments to UK legislation to make them relevant to today's society.
Summary	A number of limitations in drought management and hosepipe bans were identified during the drought event of 2004–2006: • lack of clarity about the stages of drought planning and corresponding actions; • confusion over the allowed and disallowed activities, and cynicism as to why certain activities are permitted and others not; • lack of flexibility for improvements in technology; • lack of concessions; • lack of consistency between companies allowing different interpretations, which is confusing for consumers. The following amendments were been proposed: • clearly defined drought stages and associated actions to reduce non-essential use; • consistency of interpretation by water companies; • introduction of time-based bans both by day of week and time of day to maximise effectiveness of water usage; • introduction of the ability to ban the use of water on hard surfaces and for the filling of swimming pools; • widening the scope of the ban on the washing of motor vehicles to include other consumer vehicles; • recognition of new technologies that minimise water consumption; • concessions for the elderly and disabled and for newly landscaped gardens and turf laying. The report contains a number of examples of drought restrictions in other countries such as Australia. It envisaged that the clearer and more consistent restrictions will foster more understanding among consumers.
Key points	It is important to consult on the amendments to generate consensus among stakeholders.
Data issues	
Comments	

Appendix B Further information on case studies

Table B.1 Bedford Ouse at Offord [1]

Elevation			Geology		Land use	
Min (m)	Max (m)	Weighted (m)	Type	%	Type	%
4.7	247.3	83.8	High permeability (fissured)	9.8	Sea/unclassified	0.0
			Moderate permeability (fissured)	26.4	Woodland	9.1
			High permeability (intergranular)	9.2	Arable & horticulture	56.2
			Moderate permeability (intergranular)	0	Grassland	25.6
			Very low permeability	54.6	Mountain, heath, bog	0.3
			Mixed permeability	0	Built-up areas	8.5
					Water (inland)	0.4
					Coastal	0.0

Notes [1] Adapted from Catchment Spatial Information, National River Flow Archive, CEH (http://www.ceh.ac.uk/data/nrfa/catchment_spatial_information.html)

Table B.2 Exe at Thorverton [1]

Elevation			Geology		Land use	
Min (m)	Max (m)	Weighted (m)	Type	%	Type	%
27.9	513.7	246.3	High permeability (fissured)	0	Sea/ unclassified	0.0
			Moderate permeability (fissured)	4.2	Woodland	15.1
			High permeability (intergranular)	0	Arable & horticulture	12.4
			Moderate permeability (intergranular)	10.8	Grassland	67.1
			Very low permeability	85.0	Mountain, heath, bog	2.9
			Mixed permeability	0	Built-up areas	2.3
					Water (inland)	0.2
					Coastal	0.0

Notes [1] Adapted from Catchment Spatial Information, National River Flow Archive, CEH (http://www.ceh.ac.uk/data/nrfa/catchment_spatial_information.html)

Appendix C Drought metrics and reconstructed records

n-month rainfall and runoff deficiencies

One of the simplest approaches to characterising drought is to examine rainfall or runoff deficiencies, i.e. the extent to which rainfall or runoff for a given period falls below the long-term average (LTA). Such techniques have been widely used in the literature to establish the severity of droughts or periods of low flow (e.g. Cole and Marsh 2006, Jones et al. 2006a).

A common approach is to accumulate monthly rainfall or runoff totals over an *n*-month period (e.g. 12-months, 24-months, 36-months) and then express these as a percentage of the long-term average, before ranking non-overlapping *n*-month periods.

Similarly, the approach can be used for seasonal rainfall or runoff. Rather than ranking any *n*-month periods, under this approach a fixed window is used (e.g. November to April). This is particularly useful in the context of the present study as it allows an assessment of deficits in winter rainfall (and associated runoff deficits) taken to be a principal cause of multi-year drought episodes. As the emphasis is on multi-year droughts, the two- and three-year averages of successive winters are employed in this study.

Drought Severity Index

Bryant et al. (1994) developed a Drought Severity Index (DSI) based on accumulated rainfall or runoff deficiencies. In this approach, monthly values are first expressed as an anomaly relative to a baseline period (e.g. Bryant et al.1994 used the 1951–1980 means; Fowler and Kilsby 2002 used 1961–1990). The index is then defined by the cumulative monthly deficiency. A ‘drought’ starts when a period of negative deficiency begins and the negative deficits are accumulated month-by-month until some ‘termination criteria’ is reached. Bryant et al. (1994) set this criterion to be three months of above average flow. This approach was also applied to long rainfall records by Mawdsley et al. (1994) and to long reconstructed flow records by Jones and Lister (1998). Phillips and McGregor (1998) and Fowler and Kilsby (2002) used both three- and six-month termination criteria when examining water resources droughts in south-west England and Yorkshire respectively. In the present study, a three-month termination criterion was applied and anomalies were based on the full period-of-record rather than a fixed period.

One of the issues associated with this approach, which is acknowledged by the authors who developed the mechanism, is that it relies on relatively arbitrary termination criteria. The method is clearly sensitive to the criterion used – particularly if there is a relatively wet interlude to a long duration drought – and different termination criteria would lead to different impressions of drought severity. Furthermore, as with any method that employs a ‘baseline’ period against which to compare, the choice of period is also likely to be influential. While the method does allow drought duration to be indexed as well as severity, it is important to remember that the duration of events is highly dependent on the termination criteria used.

Mawdsley et al. (1994) noted that the measure should be used as an illustrative device rather than a strictly objective measure. Accepting these caveats, the cumulative deficit index does provide an intuitive and transparent approach for identifying longer droughts, as runoff deficiencies can develop over several years.

Threshold level methods

To enable the duration of a drought episode event to be defined, a threshold level can be introduced (Figure C.1) which defines the start and end of the drought as a period when the streamflow is below a certain value or threshold, i.e. in a deficit situation. Drought characteristics thus derived include drought duration (d) (run-length), volume (v) and the minimum flow (Qmin).

The threshold level can be chosen as a percentile of the flow duration curve; here Q70 and Q90 are applied.[11] The threshold approach can be applied to daily or monthly data.

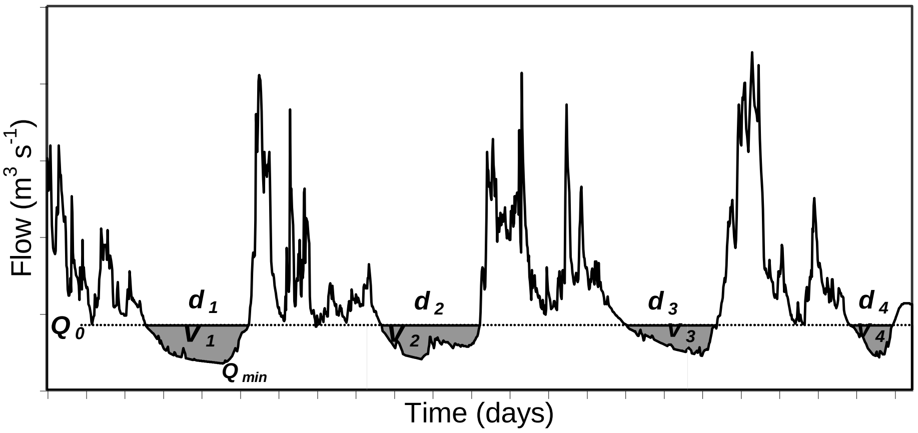

Figure C.1 Drought characteristics as defined by the threshold level method for daily time series (from Hisdal et al. 2004)

One of the disadvantages of the conventional threshold approach is that in a majority of UK rivers periods of flow below Q70 or Q90 occur primarily in the summer; droughts therefore rarely occur over a number of seasons, except on very permeable catchments. An alternative approach can be used which applies a different threshold for each month of the year; as the monthly deficit is based on typical conditions for that month, this method allows multi-season droughts to develop. In the present study, the monthly threshold approach was adopted.

The threshold method can also be regionalised using a Regional Deficiency Index (RDI) (Stahl and Demuth 1999). Under this approach, a daily varying threshold is used to generate at-site deficiency series which indicate whether the daily runoff values are below a threshold or not; for a given region, the RDI is the proportion of catchments which are under deficiency on a given day. The RDI has been used within the spatial coherence project to create a hydrological drought catalogue and is discussed in more detail by Lloyd-Hughes et al. (2010).

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[11] Defined as the flow exceeded for 70 and 90 percent of the time.

Sequent peak algorithm

Although originally applied to water reservoir engineering projects, the sequent peak algorithm (SPA) (Vogel and Stedinger 1987) has more recently been used as a drought deficit indicator (e.g. Tallaksen et al. 1997).

To calculate a deficiency time series from streamflow record, the SPA uses:

$$w(t) = \begin{cases} w(t\text{-}1) + Q_z - Q_t & \text{if} \quad w(t\text{-}1) + Q_z - Q_t > 0 \\ 0 & \text{if} \quad w(t\text{-}1) + Q_z - Q_t \leq 0 \end{cases}$$

where:

w(t) is the deficit at a given time step

Qz is the threshold level below which deficit flow occurs

Qt is the discharge at that time step (Fleig et al. 2006).

If the discharge at time step t (Qt) is less (more) than the threshold level (Qz), the accumulated deficit [w(t)] will increase (decrease).

Drought extent is defined by the period over which w(t) is positive (non-zero), although this is not to be confused with drought duration, the period between the beginning of flow deficiency and the maximum deficit. This maximum deficit [max{w(t)}] in a given drought event represents the drought deficit volume, vi. These characteristics are illustrated in Figure C.2.

The SPA method does not allow for any accumulation of ‘negative deficits’ when flow conditions are above the threshold; regardless of both how much time has passed since the last drought episode and how much water has accumulated, a new drought event begins from the moment the time series returns to a level below the threshold (Hisdal et al. 2004).

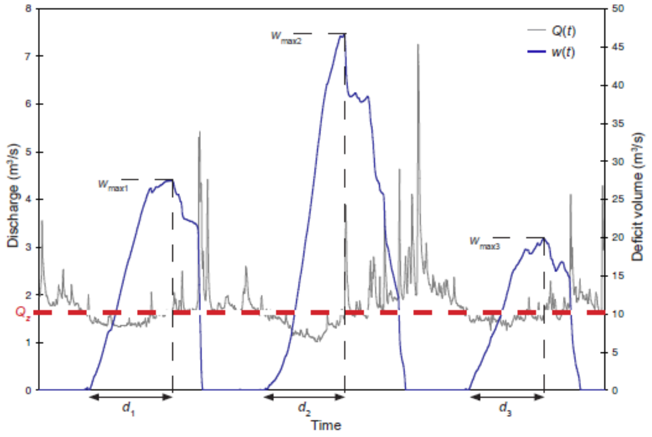


Figure C.2 Definition of the deficit characteristics (d) and deficit volume (wmax) (from Fleig et al. 2006)

There are a number of problems associated with the sequent peak algorithm. First, analyses performed on flow time series by SPA tend to highlight many very minor drought episodes (e.g. events which last only one time step) regardless of the threshold level employed. A second significant problem is the non-conveyance of some apparent droughts should they occur after major events but before deficits have recovered to exceed the threshold. This issue is related to the (not necessarily true) assumption of the SPA that the time immediately following a major episode is less prone to drought (Fleig 2004). It may in fact be argued that continued drought conditions, albeit at reduced severity, are more likely after major events given the persistence often demonstrated by drought-sustaining climatological conditions. In attempt to reduce the impact of this second problem, SPA is applied with a low threshold in order to minimise the time and deficit required to highlight multiple seasonal droughts in a time series (Fleig et al. 2006).

Meteorological indicators

The Palmer Drought Severity Index (PDSI) is a measure of regional soil moisture availability that has been used extensively to study droughts in the USA and, more recently, in other parts of the world, including on a European scale (van der Schrier 2006, Briffa et al. 2009). Hisdal et al. (2004) provide a brief introduction to the PDSI.

The PDSI is based on a complex water budget system with many parameters and is most effective in indexing drought from the perspective of soil moisture (primarily agricultural drought). The index has generally been used for classifying summer moisture availability, so droughts identified in existing work are not necessarily long droughts. Similarly, Cole and Marsh (2006) employ an ‘aridity index’ which is useful for identifying summer droughts, but has less utility for indexing winter droughts or protracted periods of rainfall deficiency. Consequently, the PSDI and aridity index were not used within the present study.

The Standardised Precipitation Index (SPI) (McKee et al. 1993) is increasingly used as an indicator of meteorological drought. SPI was used in the Environment Agency project on the spatial coherence of UK and European droughts, and is described by Lloyd-Hughes et al. (2010). It can be accumulated over any *n*-month period.

For the present study, existing SPI time series were considered as a way of indexing long droughts. These were taken from the spatial coherence project (Lloyd Hughes et al. 2010) and are based on gridded rainfall data. To allow an assessment at the two case study catchments, two time series were used – South West UK and South East UK. A regionalised version (rSPI) can be used to express the proportion of a region under an SPI of a given value.

Derivation of reconstructed runoff records

Long reconstructed river flow records available from the 1860s for 15 catchments in England and Wales (Jones and Lister 1998) were recently updated to 2002 (Jones et al. 2006a). Reconstructed records on the Exe therefore extend from 1865–2002, whereas on the Ely Ouse the record was extended back to 1800 during the earlier ‘severe’ droughts project (Wade et al. 2006).

The process of river flow reconstruction is described in detail by Jones (1984) and the updating of the records to 2002 by Jones et al. (2006a) (see Appendix F). In essence, the procedure involves hindcasting monthly average river flows using empirical models to estimate flow as a function of effective rainfall.

Clearly, there are important caveats to consider when using such synthetic series. The homogeneity of the reconstructions are sensitive to a number of sources of possible error (discussed by Jones et al. 2006a) such as errors in flow naturalisation and changes in the number of source raingauges. The latter point may be influential in the early 19th century; there were fewer gauges in the Ely Ouse catchment before the 1830s, which increases the likely uncertainty, but after this date raingauge distribution is thought to be stable (Jones et al. 2006a). A further issue is the assumption of constant actual evaporation employed by the model; while this is a reasonable assumption (see Jones et al. 2006a), it may clearly be influential on modelled estimates, particularly for extremes like droughts.

In general, the reconstructed flows are highly indicative of historical riverflows and have achieved good modelled accuracy (including independent verifications) in published work (Jones and Lister 1998, Jones et al. 2006a,b).

The reliability of the procedure for estimating historical river flows is exemplified by the analysis carried out by Jones (1984), who observed a good fit between the model and a set of observed flows available for the Exe from 1907–1911. However, it must be borne in mind that the reconstructed flows are estimates and there will inevitably be a degree of uncertainty associated with them – particularly for the early 19th century flows.

Appendix D Grafham water resources model

A spreadsheet model was developed to simulate Grafham's yield for the workshop with Anglian Water on 2 March 2009. The model calculates reservoir levels and demands with and without a range of supply- and demand-side interventions which would be implemented as part of the company's drought plan.

This appendix describes the set up of a simple Microsoft® Excel water resources model for Grafham reservoir which was developed for the project workshop with the Environment Agency and Anglian Water.

The model set up is based on a similar daily model used in the earlier 'severe' droughts project and has been shown to produce identical results to OSAY, Anglian Water's own water resources system model.

Following a review of observed and modelled flows at Offord, changes were made to the reconstructed flow series used to provide an improved estimation of source yield, consistent with Anglian Water's 2008 drought plan.

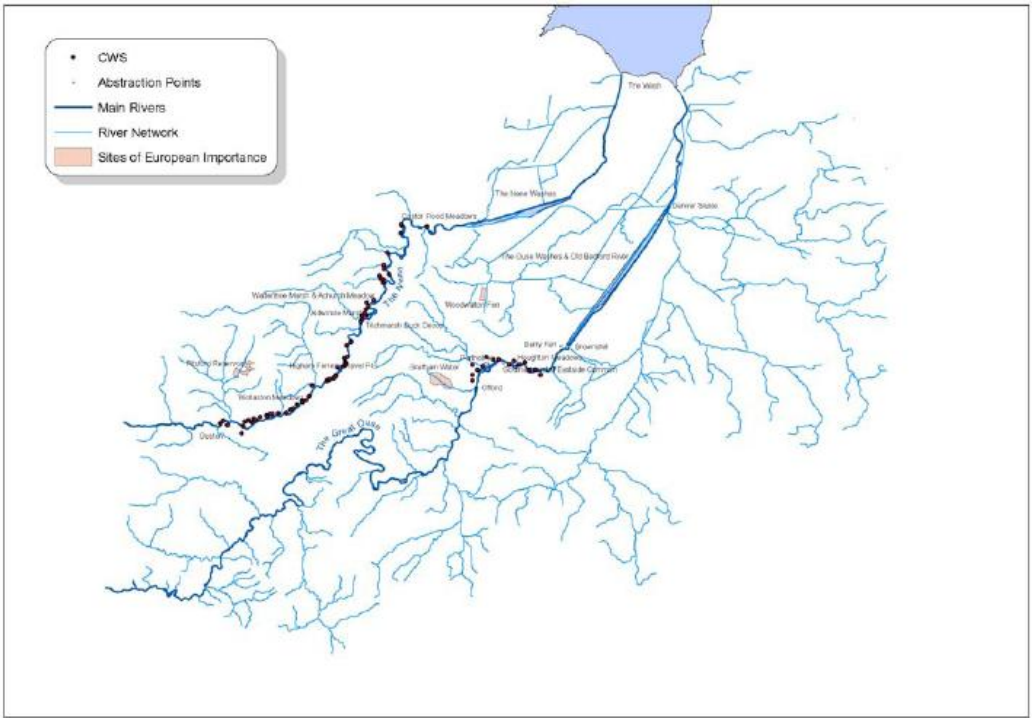


Figure D.1 Location of Grafham, abstraction points and sites indentified in the 2006 drought monitoring plan (Codling and Mistry 2006)

Water resources model

The water resources model calculates reservoir volumes at the end of each monthly time step and the average 'demand met' by considering river flows, monthly demand factors, reservoir volumes, pump capacity, minimum residual flow (MRF) and requirements for compensation flow. It calculates a 'no restrictions' yield as a baseline but also allows for supply and demand interventions each month as part of the drought management plan. The most important parameters are summarised in Table D.1.

Table D.1 Grafham reservoir parameters

Key data	
Reservoir parameters	**Value**
Pump capacity (Ml/d)	485
Licence – maximum daily abstraction (Ml/d)	485
Gross volume (Ml)	55,494
Dead storage (Ml)	2627
Emergency storage (Ml)	30 days × yield
Net reservoir volume (Ml)	52867
Freshets/compensation flow (Ml/d)	5.5
Target yield (Ml/d)	245.0
Start volume	100%
Minimum residual flow at abstraction point (Ml/d)	136.00 – calculated : 136 + 0.25 (flow –136)

Table D.2 lists the monthly demand factors used.

Table D.2 Monthly demand factors for Grafham

Month	Demand factor	Demand with no restrictions (~annual average 245 Ml/d for 'Scenario 1')
1	1.00	245.0
2	1.00	245.0
3	0.97	237.7
4	0.97	237.7
5	1.00	245.0
6	1.06	259.7
7	1.11	272.0
8	1.07	262.2
9	0.95	232.8
10	0.92	225.4
11	0.95	232.8
12	1.00	245.0

As the model uses a monthly time step it does not consider peak week demands.

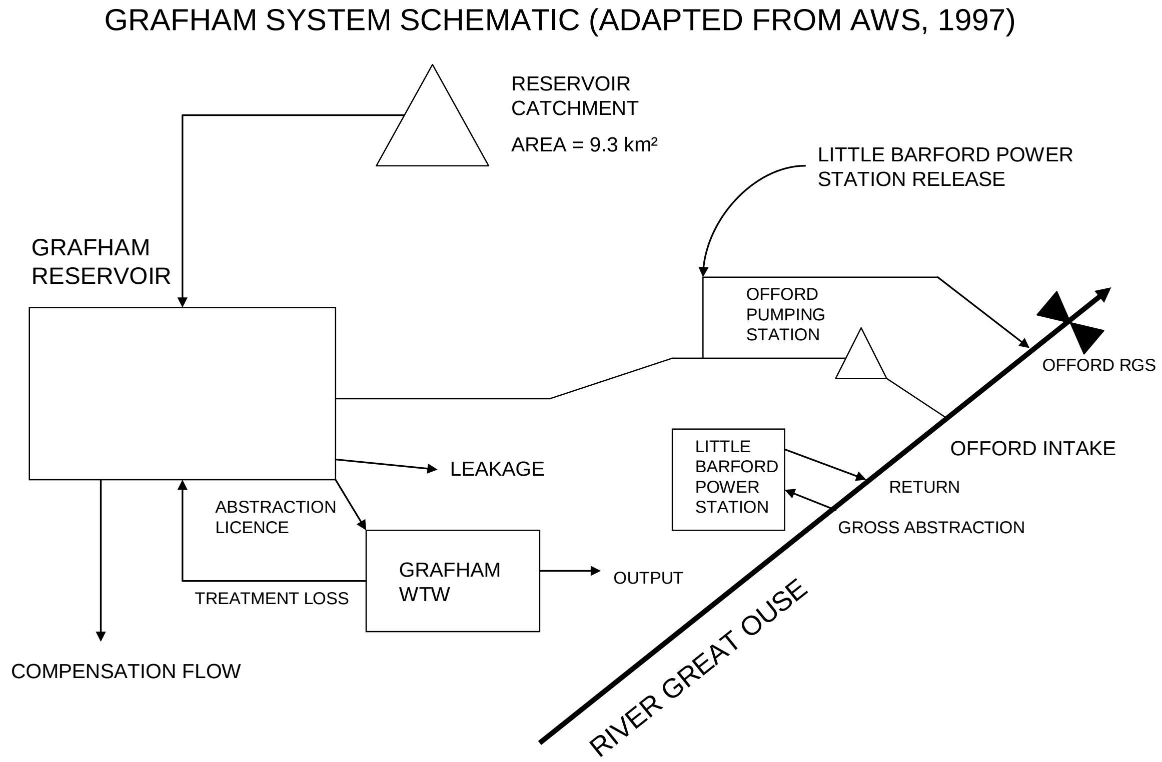


Figure D.2 Schematic of the water resources system for Grafham

A schematic of the water resources system is given in Figure D.2. The model logic considers that:

- water is available at Offord when flows are greater than the MRF and flow above the MRF is available for pumping up to the pump capacity;
- the amount of water pumped is based on the ‘space available’ plus water supply and environmental demands (the calculation considers maximum reservoir volume, reservoir volume in the previous time step, demand, compensation flow and natural inflows);
- the reservoir volume is the balance of all components and the system ‘fails’ when the target demand can not be met.

The drought measures used can be changed during the workshop and are not ‘hard wired’ into the spreadsheet. Hence interventions are flexible in terms of timing, duration and quantity (demand reduction/supply). All drought measures used are based on Anglian Water’s drought plan. Feedback from the company’s water resources team on an earlier draft was taken into account in drawing up the table of drought measures shown in Figure D.3.

Figure D.3 Table with drought measures for Grafham

	Nr		Demand/Supply.Opps/Other	No	Additional reduction in demand %	Cumulative reduction %	Average pcc l/h/d	Additonal supplies (DO) Ml/d	Cumulative additional supplies Ml/d	Lag (months)	Max Duration (months)	Comments
Drought Alert Curve	1	Enhanced communications	D	1	1%	1%	138.6	0	0	0		
	2	Supply-side actions	S	2	0%	1%	138.6	0	0	0		
	3	Operational actions	O	3	0%	1%	138.6	0	0	0		
	4	Regulatory actions	R	4	0%	1%	138.6	0	0	0		
Trigger Curve 1 (1:10)	5	Communications strategy increased.	D	5	5%	6%	131.6	0	0	0	unlimited	Lower estimate of effectiveness of comms. Strategy.Publicity campaign to inform customers of the situation, including whether any demand restrictions are in place. Also increase promotion of water efficiency. Demand savings of 5 to 10 %
	6	Enhanced leakage control.	D	6	1%	7%	130.2	0	0	1	unlimited	Assumption of 1% demand reduction = 2.45 or 2.62 Ml/d for Scenario 1 and 3 respectively. 1-4 weeks to prepare. Effective for the duration of the potential/drought period
	7	Hosepipe bans.	D	7	3%	10%	126	0	0	1	6	Hand in hand with communications is 8%. Demand savings of 3 to 12 %. 2 weeks to prepare. Effective during the drought period. Most effective during periods of high demand. Based on consideration of the need to conserve water in the area.
	8	Local emergency supplies e.g. pipes and boosters.	S	8	0	10%	126	0	0	1	unlimited	Would take 1-4 weeks to prepare and would be a temporary measure during drought period. Would be effective all year round and give a small DO.
	9	Drill/Commission satellite boreholes	S	9	0	10%	126	0	0	5	unlimited	Would take 4-6 months preparation. They would be effective all year round and once commissioned are available permanently. Would sustain DO. Would impact on AW Borehole replacement programme.
	10	Review of Bulk Supplies with neighbouring water company	S	10	0	10%	126	0	0	2	unlimited	Would take 1-3 months to prepare and 2-6 months to implement. Would be effective all year round and could be a temporary or permanent measure. DO would depend on local availability.
	11	Review use of Foxcote Reservoir	S	11	0	10%	126	7	7	14	unlimited	An unused licensed source. Would take 1-2 months to prepare and 1 year to implement scheme - unlikely to be practical during drought. Could be a temporary or permanent measure and would be effective all year round. DO would be 12 Ml/d peak.
Trigger Curve 2 (1:40)	12	Increase communications and publicity	D	12	5%	15%	119		7	0		
	13	Restrictions on non-essential uses.	D	13	5%	20%	112	0	7	2	3	1-3 months to prepare including the application for a Drought Order. Maximum duration = 3 months unless an extension is required. Most effective during seasons of high demand.
	14	Reduction of MRF at Offord.	S	14	0	20%	112	10	17	6	?	Sustain DO. Used for WINTER only.
Trigger Curve 3 (1:100)	15	Standpipes or rota cuts.	D	15	20%	40%	84	0	17	2	3	Cumulative demand savings of 34 to 52 %. 1-3 months to prepare including the application for a Drought Order. Maximum duration = 3 months unless an extension is required. Effective all year round.
	16	Take Dead Storage	S	16	0	40%	84	29	46	1	3	Take all dead storage over 90 days.
	17	Tankers	S	17	0	40%	84	1	47	1		NOT IN DROUGHT PLAN. 30000 litres per truck, 33 trucks a day = 1 Ml/ d
	18	Bottled Water	S	18	1%	41%	82.6	0.5	47.5	0		

Deployable outputs

The crucial figures for Grafham's yield with no restrictions (scenario 1) and with restrictions (scenario 3) simulated from 1920 are shown in Table D.3.

Table D.3 Deployable outputs for Grafham

	Deployable output	Critical years
Anglian Water's 2008 drought plan (scenario1)	245 Ml/d	1934–1976
Anglian Water's 2008 drought plan (scenario 3)	262 Ml/d	1934–1976
Monthly model		
Based on observed flows from 1970	245 Ml/d	1976
Factored pre-970 and observed from 1970	238 Ml/d	1934–1976 [1]
Factored flows	238 Ml/d	1922–1934
Regression	300 Ml/d	1934–1922

Notes [1] If a target yield of 245 Ml/d is applied to the monthly model with combined factored and observed flows for Offord from 1970, the reservoir fails in both 1922 and 1976 for a total of five months.

The spreadsheet modelling shows that the yield is highly sensitive to the choice of flows at Offord and is influenced by switching from a daily to monthly time step. In addition, the critical years of 1933–1334, 1975–1976 and 1922 are fairly close and switch order with different flow series.

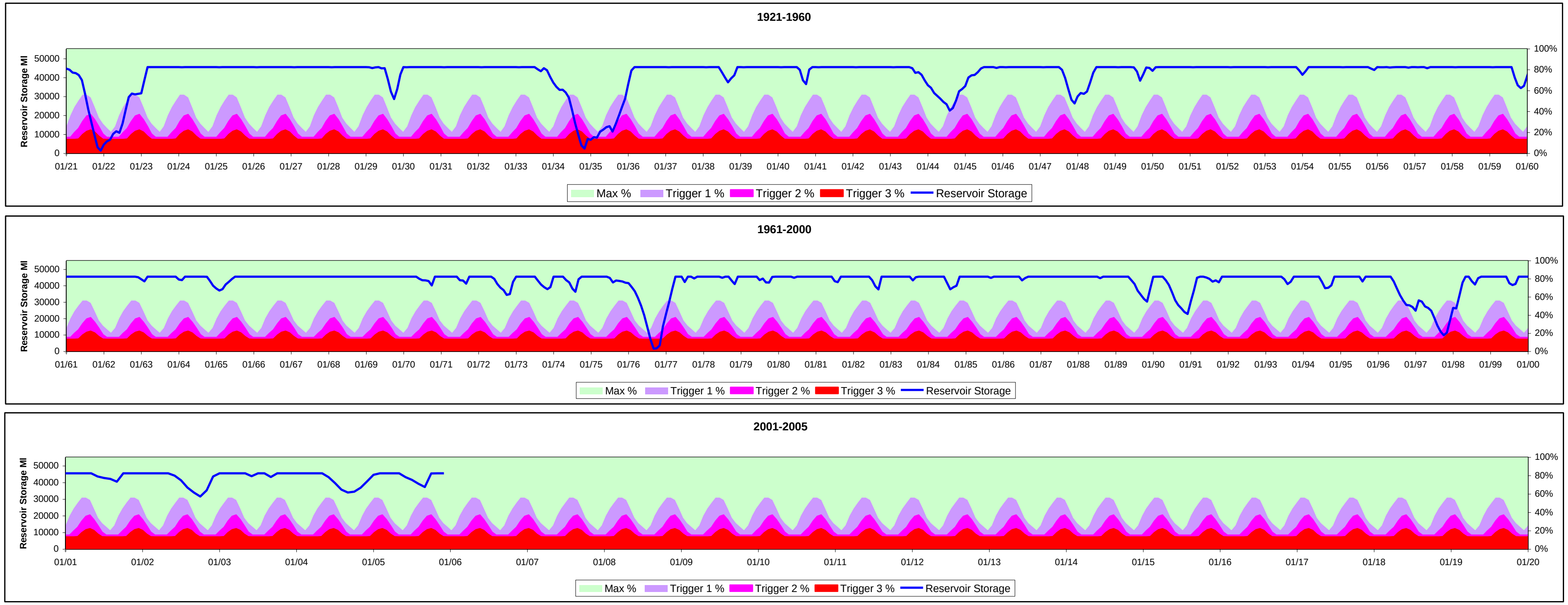
The factored flows produce the most realistic yield for Grafham and therefore these were used for the workshop examples of long droughts.

Figure D.4 shows example outputs for the monthly model for Grafham.

Figure D.4 Example outputs of monthly model for Grafham

Target yield: 245 Ml/d

Scenario 1 (no restrictions)



Flow series

Application of the reconstructed flows from the earlier 'severe' droughts project led to a significantly higher yield for Grafham than Anglian Water's modelled flows. This was understood to be due to a range of uncertainties in the modelling (both Anglian's and the research projects) and transposition of reconstructed flows from Denver to Offord where water is abstracted for Grafham. This work was revisited as part of this study. The following river flow time series were reviewed:

- Jones et al. (2006a) reconstructions at Denver sluice and transposition to Offord;
- Anglian Water's modelled flows from 1918–2003 based on the Stanford Watershed Model (SWM);
- observed flows from Denver sluice and Offord from the National Water Archive.[12]

As a result, two new records were constructed for Offord:

- reconstructed Offord flows based on monthly flow factoring from the reconstructed record at Denver sluice to give the same average monthly flows as the Anglian Water simulated series;
- reconstructed Offord flows based on a new regression of Offord observed versus reconstructed flows at Denver sluice. For flows above seven cumecs, the regression was reasonably good (R^2 = 77 per cent) but below this threshold the relationship was poor (R^2 = 55 per cent) (Figure D.4).

This provided new reconstructed flows for this study which produced realistic yields. Further work was possible (and would be beneficial) based on rainfall–runoff modelling using long-term rainfall and temperature datasets at Offord but this was outside the scope of this study.

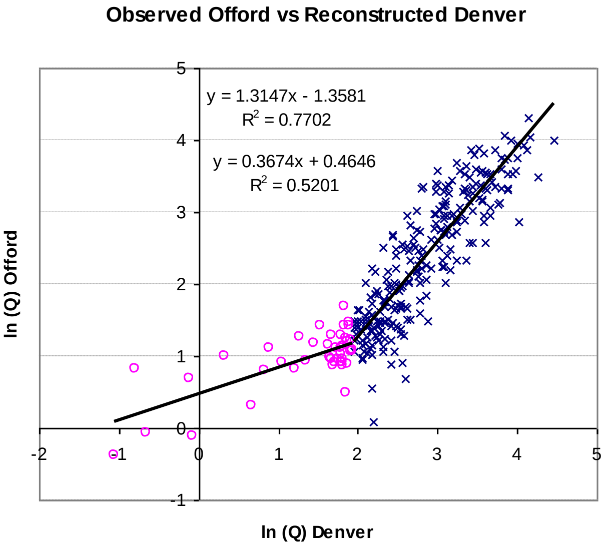


Figure D.5 Observed Offord flows versus reconstructed flows at Denver sluice

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[12] The Denver NWA record is patchy and incomplete. Further data are needed from the Environment Agency to complete the record.

Appendix E Wimbleball water resources model

A spreadsheet model was developed to simulate Wimbleball's yield for the project workshop with South West Water on 29 February 2009. The model calculates reservoir levels and demands with and without a range of supply- and demand-side interventions that would be implemented as part of the company's drought plan.

This appendix describes the set up of the simple Microsoft® Excel water resources model for Wimbleball reservoir located in South West Water's Wimbleball strategic supply area (SSA) (Figure E.1). The model was set up based on naturalised flow time series, licence and reservoir information provided by South West Water.

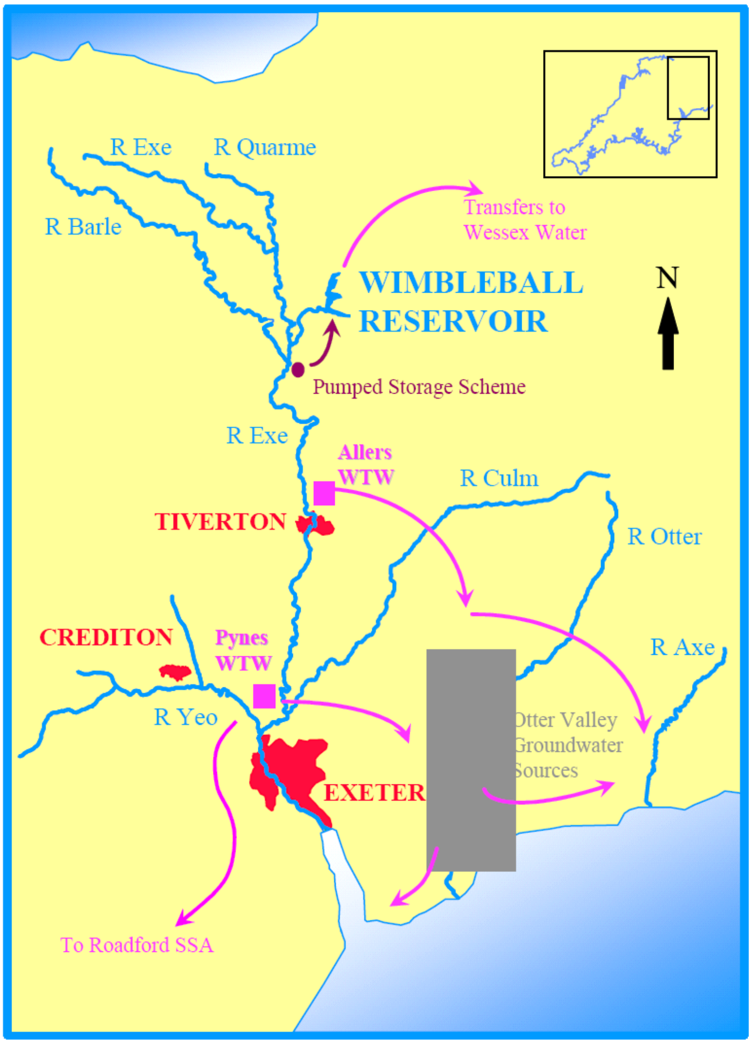

Figure E.1 Transfers and abstraction points for Wimbleball (South West Water 2007)

Wimbleball reservoir

Wimbleball reservoir is used mainly to augment riverflows in the summer for abstraction downstream on the River Exe. The water is mainly used for public water supply in Wimbleball SSA but is also used for water transfers to Wessex Water. The reservoir inflows and outflows taken into account in the model are illustrated in the schematic in Figure E.4. Licence information is listed in Table E.1.

Table E.1 Wimbleball reservoir pumped storage licence data

Licence	Daily licence (Ml/day)	Annual licence (Ml)	Additional comments
Wimbleball PS	150	13,633 (Jan–Dec)	Abstraction between 1 November and 31 March only
			Prescribed flow = 1.16 m^3/s, 50% take
			Annual fisheries bank = 900 Ml
			No abstractions for PS at the same time as making releases from Wimbleball
			Wimbleball PS is modelled at a maximum abstraction rate of 135 Ml/d. This is less than the maximum licensed abstraction to account for operational contingencies.
			Modelling does not take account of shutdown due to water quality.
Wimbleball release		12,585	
River Exe at Northbridge Licence of Right (for Pynes WTW, Exeter)	24.457	8,926.8	Licence of Right
River Exe at Northbridge (for Pynes WTW, Exeter)	42	14,300	Prescribed flow = 3.16 m^3/s at Thorverton GS (based on Thorverton natural flow)
River Exe at Bolham (for Allers WTW, Tiverton)	32	11,564.5	When the natural flow in the River Exe at Thorverton is 3.16 m^3/s or less, abstraction is restricted to 2.7 Ml/d excluding water discharged from Wimbleball to the river for public water supply abstraction.

River flow series

For simplicity, the model uses a monthly time step and all available daily and weekly data have been converted to monthly values.

Monthly river flows for the model (1865–2006) were constructed based on naturalised daily flows provided by South West Water and a monthly flow reconstruction by Phil Jones for Thorverton GS. Naturalised flows by South West Water were used from 1957–2006 and from 1865–1956 regression analysis was undertaken to construct flow records for Exebridge and Wimbleball based on Phil Jones' Thorverton flows.

Linear regressions were undertaken using the daily flows provided by South West Water and applying the correlations to Phil Jones' data. The coefficients of determination (R^2) were between 0.97 and 0.98.

A check on the reconstructed flows provided by Phil Jones revealed a general underestimation of flow volume at Thorverton by approximately 5 per cent compared with flows provided by South West Water. The Thorverton record was therefore scaled up by this amount before applying the regressions to produce flows at Exebridge and Wimbleball for 1865–1956.

As a check on the validity of this approach cumulative flows, scatter plots and flow duration curves for the overlapping period were produced at the three sites to check consistency between the flows. As an additional check, regressions were also produced between the monthly Jones data and South West Water monthly flows directly with almost identical results.

Water resources model

In the model, riverflows at the Exebridge intake and Thorverton are taken as the naturalised Exebridge and Thorverton flows. However, the available flow for abstraction at Exebridge is somewhat lower due to fish farm abstraction upstream of the intake; this is taken into account in the model calculations as illustrated in the schematic shown in Figure E.4.

The main assumptions used in the model are listed below:

- The river flow at Exebridge is taken as naturalised Exebridge flow.
- Available flow for abstraction (pumped storage) is assumed to be the Exebridge flow minus abstraction at the fish farm with a prescribed flow (pf) of 100.65 Ml/d and allowance of 50 per cent above pf.
- Compensation flow was set to 9.1 Ml/d.
- The net reservoir volume available is 21,320 Ml/d and failure to meet demand will occur when the reservoir runs empty.
- Fisheries bank abstraction is taken as 450 Ml in August and September (900 Ml in total).
- Abstraction at Exebridge is allowed between 1 November and 31 March. It is assumed that abstraction occurs at a maximum rate of 150 Ml/d up to an annual maximum of 13,666 Ml. Once the annual licence is reached no further abstraction can take place.
- Actual pumping is assumed to be 135 Ml/d rather than 150 Ml/d to account for operational contingencies.
- Abstraction will only occur if the reservoir volume for the previous month falls below an operational trigger level (volume) provided by South West Water.
- In case the reservoir fills above the maximum level due to Wimbleball natural inflows, the additional volume is assumed to overspill downstream of the intake.
- Two different demand profiles were included with similar results: one based on Wessex demand and one taken from the WRMP for Wimbleball SSA. The Wessex demand profile was used in the final model.
- Surface water abstraction at Northbridge and Bolham is calculated based on flows at Thorverton. If the naturalised flow drops below the prescribed flow, abstraction is limited to 2.7 Ml/d plus 24.457 Ml/d of the naturalised flow and the remaining water is provided by Wimbleball releases.

- Maximum demand is taken as the water treatment works capacities plus Wessex demand and comes to ~135 Ml/d.

Some of the licence information could not be included in the model on a monthly time step:

- Shutdown due to water quality has not been taken into account but should have limited effect on the reservoir DO as shutdown only tends to occur for short periods (days) during wetter periods.[13]
- Abstraction for the fish farm is spread out over a full month rather than over a few days, which will have an effect on the modelled drawdown.

The drought measures used can be changed during the workshop and are not 'hard wired' into the spreadsheet. Hence interventions are flexible in terms of timing, duration and quantity (demand reduction/supply). All drought measures used are based on South West Water's drought plan. Feedback from the company's water resources team on an earlier draft was taken into account when producing the table of drought measures shown in Figure E.2.

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[13] In Miser, it is assumed that if the flow in the river rises above 1,400 Ml/d, the intake is switched off for two days. However if during these two days the level falls below 1,400 Ml/d again, abstraction can commence immediately. If the river level rises above 2,000 Ml/d, no abstraction can take place under any circumstances.

Figure E.2 Table with drought measures for Wimbleball [1]

	Nr		Demand/Supply.Opps/Other	No	Additional reduction in demand %	Cumulative reduction %	Average pcc l/h/d	Addiitonal supplies (DO) Ml/d	Cumulative additional supplies Ml/d	Lag (months)	Max Duration (months)	Comments
Zone A: Drought Alert Curve	**1**	Normal customer communications	D	1	0%	0%	150			0		
	2	Supply-side actions	S	2		0%	150			0		None listed other than support reservoirs
	3	Operational actions	O	3	0%	0%	150			0		
	4	Regulatory actions	R	4	0%	0%	150			0		
Trigger Zone B (1:10)	**5**	Communications strategy increased.	D	5	5%	5%	142.5			0	unlimited	Early Spring water supply campaign- media; weekly updates to WaterUK; letters to MPs, local authorities and other key organisations to explain situation; distributing booklets; advertising campaign if appropriate. Follow-up communications campaign- regula
	6	Enhanced leakage control.	S	6	0%	5%	142.5	2.5	2.5	1	unlimited	Leakage savings of approx. 2.5 Ml/day. 84 Ml/day total leakage target, set by Ofwat so improvemnets ongoing.
	7	Direct supply to Pynes using existing licensed sources (Stoke Cannon: 4.546 Ml/d and Bramford: 3.45 Ml	S	7	0%	5%	142.5	8	10.5	2	gwl constraint	Abstraction licences are already held for these sources and landowner permission will be needed to construct the overland pipeline. It will take 6-8 weeks to construct an overland pipeline. Duration of option can be for as long as necessary.
	8	Restart abstraction from Colwood and Knowle licensed boreholes	S	8	0%	5%	142.5	1.2	11.7	2	gwl constraint	It will take 6-8 weeks to implement and reconnection to the supply system as well as a review of treatment arrangements will be required. This option can last for as long as necessary.
	9	Restart abstractions from Uton Borehole	S	9	0%	5%	142.5	0.8	12.5	2	gwl constraint	It will take 6-8 weeks to implement and reconnection to the supply system as well as a review of treatment arrangements will be necessary. Abstraction licence is already held. The option can be used for as long as necessary.
Trigger Zone C (1:20)	**10**	Hosepipe bans	D	10	5%	10%	135	0	12.5	1	6	Hosepipe ban: assumed to give a 5% reduction in demand. Can be implemented within a week after deciding to impose the ban. High level confidence of savings. Six month maximum duration. Occurs not more than 1 in 20 years.
	11	Abstraction of the Wimbleball compensation release	S	11		10%	135	9.1	21.6	1	6	Authorisation is made through the Operating Manual and the time it takes to do this determines how long it will take to implement this measure.
	12	Use of Drought Orders or Drought Permits to reduce compensation or prescribed flows	S	12		10%	135	10	31.6	1		Prescribed flow reduction assumed to be 10% ~ 10 Ml/day
	13	Local emergency supplies e.g. pipes and boosters.	S	13		10%	135	1	32.6	1		Would take 1-4 weeks to prepare and would be a temporary measure during drought period. Would be effective all year round and give a small DO.
	14	Review of Bulk Supplies with neighbouring water company.	S	14		10%	135	3	35.6	2		Would take 1-3 months to prepare and 2-6 months to implement. Would be effective all year round and could be a temporary or permanent measure. DO would depend on local availability.
Trigger Zone D (1:40)	**15**	Restrictions on non-essential uses.	D	16	5%	15%	127.5		32.6	2	4	High confidence that savings can be achieved. Can take a long time to implement - 4 - 6 weeks from advertising. Four month maximum duration of ban on non-essential uses. Occurs not more than 1 in 40 years.
	16	Take dead Storage	S	15		15%	127.5		32.6	1	3	For 100 days ONLY
	17	Standpipes or rota cuts.	D	17	20%	35%	97.5		32.6	2		Demand savings of 34 to 52 % or 73 to 111.5 Ml/d. 1-3 months to prepare including the application for a Drought Order. Maximum duration = 3 months unless an extension is required. Effective all year round.
	18	Tankers	S	18		35%	97.5	1	33.6	1		30000 litres per truck, 33 trucks a day = 1 Ml/ d
	19	Bottled Water	S	19	1%	36%	96	0.5	34.1	0		

Notes [1] Measures highlighted in pink are not in the drought plan as they are not considered acceptable measures.

Deployable output

Based on the simplified model, the DO was assessed to be approximately 140 Ml/day for 1975–1976 – the design period used in South West Water's water resources plans; this is slightly larger than the current maximum demand (WTW capacity and Wessex demand). This is based on a daily version of the model and it was found that the DO needed to be set somewhat higher to obtain a similar drawdown using a monthly time step.

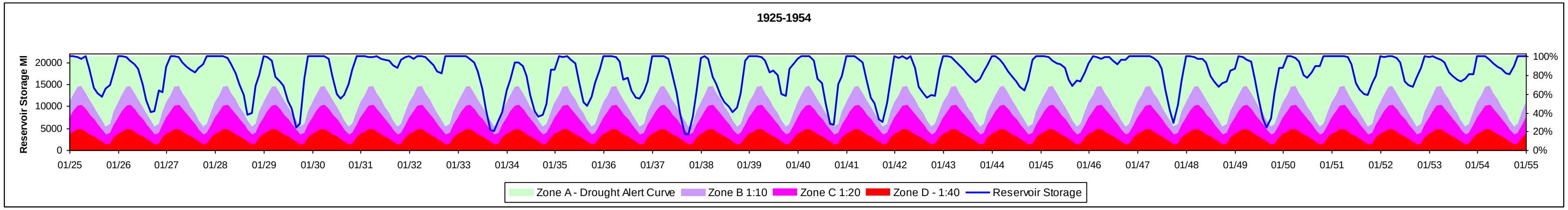
Consequently the model was used with a target DO of 150–155 Ml/day for the workshop. The difference in drawdown is due to smoothing of flows and fish farm abstraction in the dry summer months.

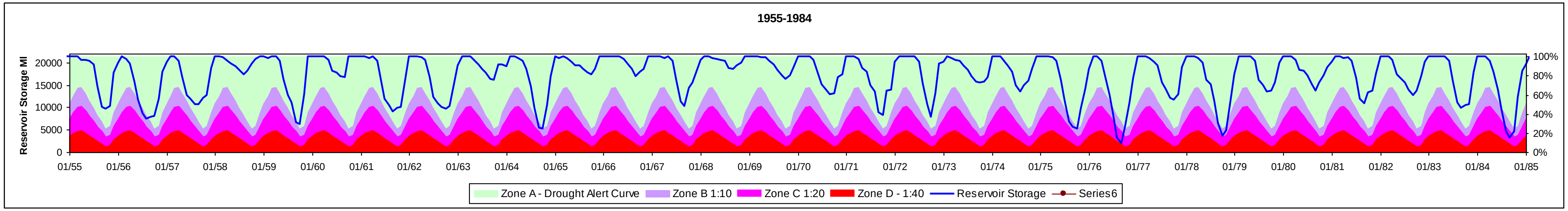
Figure E.3 shows example outputs for the monthly model for Wimbleball.

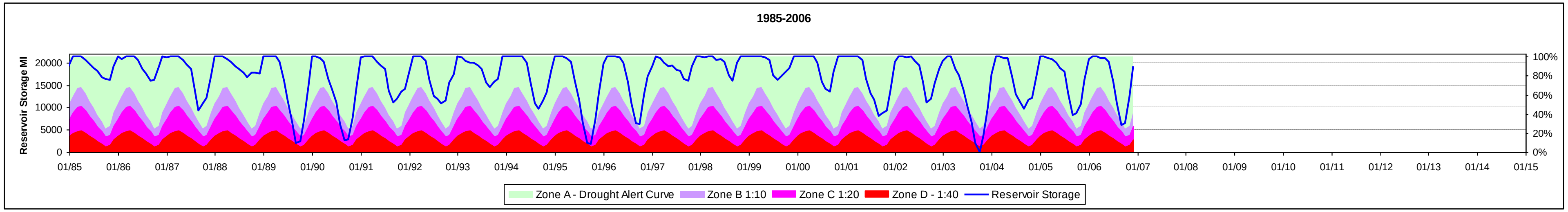
Figure E.3 Example outputs of monthly model for Wimbleball

Target yield: 150 Ml/day

Historic scenarios







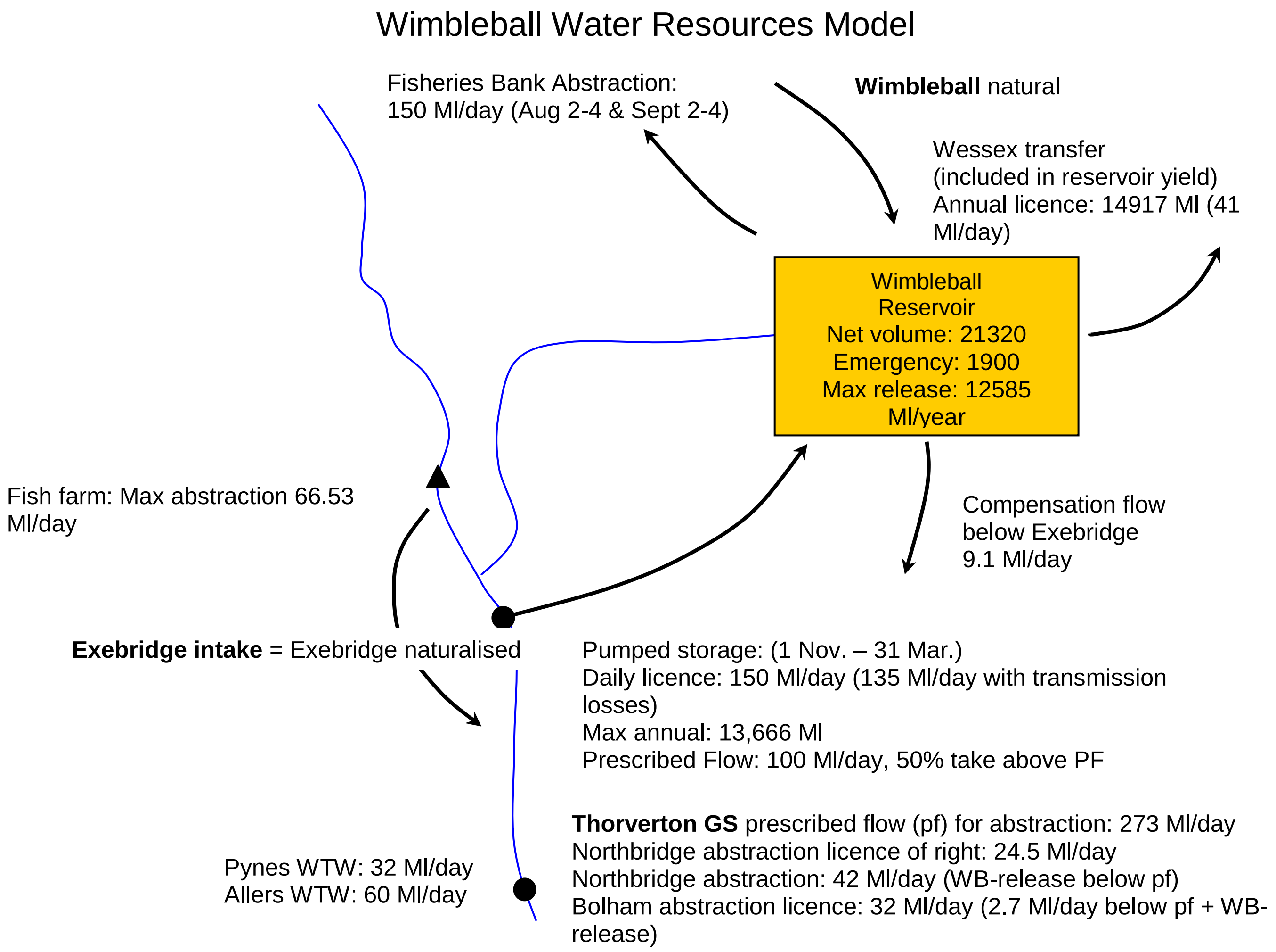


Figure E.4 Wimbleball reservoir schematic

Appendix F Guidelines for hindcasting river flow and other climate records

Apart from a number of notable exceptions, widespread river flow measurement began in England and Wales in the 1950s. Flood marks on bridges and in towns and newspaper and earlier reports of exceptional droughts often give clear examples of runoff variability that is outside of the range of that observed (Jones et al. 1984). For low flows, Jones (1984), Jones and Lister (1998) and Jones et al. (2006a) have shown that riverflows may be reconstructed at the monthly scale from the extensive raingauge network available across the country. Rainfall recording began in the UK in the 17th century and, by the mid-19th century, records were available in all but the least populated parts.

This appendix provides guidelines on climate reconstruction – particularly of areal rainfall and runoff records – and offers an overview of available data and description of different methods for extending hydrological data series. The six sections cover:

- rainfall records;
- runoff records;
- approaches to using neighbouring catchments where long records exist;
- extensions to the daily timescale;
- ancillary variables such as temperature and evaporation;
- a step-by-step guide to extending and using river flow series for water resources and drought planning.

Rainfall records

The UK has the most extensive network of rainfall recording anywhere in the world. The digital network is maintained by the Met Office and all available daily data have been digitised since 1961. Earlier daily data have been digitised as a result of exercises such as the Flood Studies Report in 1975. However, a cursory look through the rainfall archives held at the Met Office and a study of the annual volumes of *British Rainfall* (available from 1865 until publication ceased in 1991) indicates that only a small subset of the potential data before 1961 has been digitised.

The paper rainfall archives (held at the Met Office) also contain the ‘10-year books’. These comprise monthly totals for each decade up to the 1980s. Each decade was produced in real-time from the 1850s, but earlier decades back to the 1670s were developed between the 1860s and the 1970s. These records can be consulted, and have been used by many people to develop long monthly records for individual locations or for large regions and the country as a whole (Jones 1981, Jones 1983, Tabony 1980, Wigley et al. 1984). It is these data sources that were used by Jones (1984) and Jones and Lister (1998) to develop the rainfall series necessary for river flow reconstruction.

This work was labour-intensive as there is no index of the lengths of records across the various decades. The volumes of *British Rainfall* can be used to determine the longer and more continuous series, but the volumes themselves only give annual totals for years before about 1940. The data then need to be digitised and subsequently assessed for long-term homogeneity (consistency of the series through time). This latter aspect is helped by the sheets containing details of irregular site inspections from around 1900.

Recently, the Met Office has developed daily and monthly gridded datasets (at 5 × 5 km resolution) from the available digitised data (Perry and Hollis 2005a,b). The grids for monthly precipitation extend back to 1914 (Perry 2006) and are freely available for academic research use (downloadable through the British Atmospheric Data Centre[14]). The grids for daily precipitation extend back to 1958, but are only available for use if purchased. Interpolation uses eastings, northings, elevation and distance from coast (see details in Perry and Hollis 2005a,b). The daily and monthly grids have been produced independently, so in upland regions the sum of the daily grids is always less than that derived from the monthly interpolation. This arises as orographic effects are better incorporated in the monthly gridding than at the daily timescale.

A study of the number of stations used by Perry (2006) indicates that no extensive digitisation exercises have been undertaken recently and that considerably more data are available in the ‘10-year books’. Despite this, the simplest way to derive monthly areal-average series for any catchment in the country would be to use this digital archive for 1914 to the current final year of 2007. Catchment boundaries are digitally available and these have been mapped onto the 5 × 5 km grids using the software package EARWIG developed for the Environment Agency by Kilsby et al. (2007). One advantage of using the Perry (2006) source is that the gridding uses elevation and so should provide the true average rainfall for the catchment to be studied. This might be particularly important in upland regions where many of the gauges are likely to be located in the valleys.

Study of low-flow periods in the reconstructed series from Jones et al. (2006a) indicates a number of extended low-flow sequences in the late 1880s and particularly in the 1890s. Extending areal rainfall series back to 1914 does bring in the severe drought of 1921 and others in the early 1930s, but the earlier work clearly indicates that there were a number of multi-year droughts in the period from the 1850s to the 1890s (for some spatial maps of extents, see: Wright and Jones 1982, Jones et al. 1997). The Met Office has plans to extend the gridding back to earlier years (1910 is the first aim, but the eventual aim would be the 1870s), but this will take considerable digitisation efforts as there is a marked reduction in digital data before the 1910s. Extending areal catchment averages before 1914 therefore requires consultation of the ‘10-year books’ and the incorporation of an overlap with the series derived from the digital grid from 1914.

Another way of extending areal rainfall series to earlier dates would be to use the nearest of the 15 long areal rainfall series developed by Jones et al. (2006a). These all extend back to 1865 – considerably earlier for some of the catchments. The extension could use regression (separately for each month) between the two rainfall series over the period from 1914–2007 or even application of monthly anomalies (percentage changes, standard deviation or z scores) from a donor site to a target catchment. Use could also be made of the long individual site series developed by Jones (1977, 1981, 1983) and by Tabony (1980) and also of the five regional precipitation series (which extend back to 1873) for England and Wales (Alexander and Jones 2001).

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[14] http://badc.nerc.ac.uk/home/index.html

Runoff records

Runoff records were reconstructed back to 1865 by Jones et al. (2006a) for 15 catchments across England and Wales. These catchments are listed in Table F.1 and their locations are shown in Figure F.1. Further details of catchment characteristics, observed and naturalised flow series and calibration/validation exercises can be found in Jones and Lister (1997, 1998) and Jones et al. (2006a).

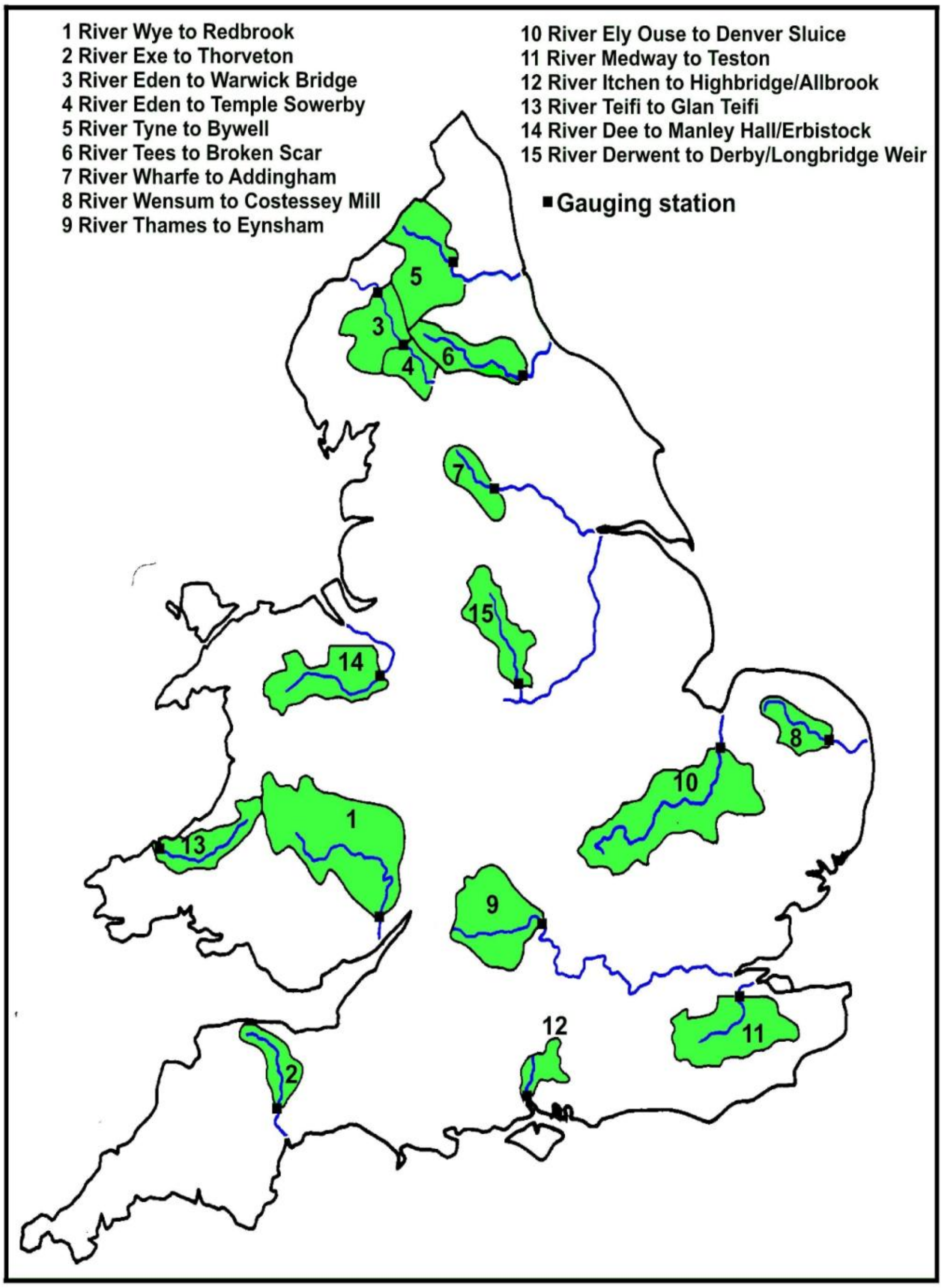

Figure F.1 Locations of the 15 catchments used by Jones et al. (2006a)

Table F.1 Details relating to catchments, catchment observed flow series (gauged and naturalised) and model calibration periods [1,2,3,4]

Catchment	Flow gauge	NGR of gauge	Area (km^2)	1961–1990 precipitation (mm)	Average flow(m^3/s)	Observed flows (NRA) used in earlier work	Observed flows (Environment Agency) used for the updating	Naturalised flows used in the updating	Parameter calibration periods
Tyne [11]	Bywell	45 (NZ) 038 617	2176	1015	45.2	1956–1993	1956–2003	1956–1993	1962–1977
Tees [11]	Broken Scar	45 (NZ) 259 137	818	1141	16.9	1956–1993	1956–2003	1956–1993	1957–1971
Wharfe [6]	Addingham	44 (SE) 092 494	427	1383	14.1	1962–1993	1973–2003	1995–2000	1964–1977
Derwent [10]	St. Mary's Bridge	43 (SK) 356 363	1054	1012	17.8	1977–1993	1935–2003	1977–1997	1977–1993
Ely Ouse [8]	Denver Complex	53 (TF) 588 010	3430	587	11.8	1926–1993	1950–2003	1980–2002	1962–1977
Wensum [9,10]	Costessey Mill	63 (TG) 177 128	571	672	4.0	1960–1993	1960–2003		1964–1974
Thames [5]	Eynsham	42 (SP) 445 087	1616	730	13.8	1954–1993	1951–2003	1955–2003	1964–1976
Medway [7,10]	Teston	51 (TQ) 708 530	1256	744	11.2	1957–1994	1956–2003	1920–1996	1970–1993
Itchen [7,10]	H.bridge+A.brook	41 (SU) 467 213	360	833	5.4	1959–1988	1958–2003	1970–2000	1969–1988
Exe	Thorverton	21 (SS) 936 016	601	1248	16.3	1956–1993	1956–2003		1958–1977
Wye [6]	Redbrook	32 (SO) 528 110	4010	1011	74.3	1937–1993	1936–2003		1956–1975
Teifi	Glan Teifi	22 (SN) 244 416	894	1382	28.9	1959–1995	1959–2003		1971–1994
Dee [5,10]	Manley Hall	33 (SJ) 348 415	1019	1369	31.2	1970–1989	1937–2003	1969–2002	1970–1989
Eden1 [5,6]	Temple Sowerby	35 (NY) 605 283	616	1272	14.4	1965–1993	1964–2003		1965–1977
Eden2 [5,6]	Great Corby	35 (NY) 470 567	1367	1146	34.0	1967–1993	1959–2002		1967–1977

Notes

[1] Modified from Jones et al. (2006a).

[2] All catchment data originate from the Concise Register of Gauging Stations (http://www.nwl.ac.uk/ih/nrfa/station_summaries/crg.html)

[3] Some values are period specific and will differ slightly from statistics given elsewhere.

[4] Flow data (for updating) originate from the Environment Agency and CEH sources.

[5] There are known problems with the gauging of high flows on the Thames, Dee and Eden1.

[6] Rating changes will/have affect(ed) observed flow series on the Wharfe, Wye, Eden1 and Eden2.

[7] Naturalisation methods have changed with potentially adverse consequences for reconstructions using original model parameters on the Medway and Itchen.

[8] There are doubts as to the homogeneity of observed flow series for the Ely Ouse.

[9] The gauged flows for the Wensum have been affected since 1988 by significant abstractions just upstream of the flow gauge.

[10] Naturalised flows were used for original model calibrations and (where possible) validations on the Derwent, Wensum, Medway, Itchen and Dee.

[11] There are significant periods of missing data within the naturalised flow series for the Tyne and Tees.

The reconstructions use the long monthly rainfall records discussed in the previous section and a statistical rainfall–runoff model developed by Wright (1978). The model is calibrated using values of the logarithms of mean monthly river flow. These are related by regression to linear combinations of data on soil moisture (estimated from precipitation and actual evaporation) and effective precipitation (precipitation minus actual evaporation) and a number of constants (for full details see: Wright 1978).

The empirical nature of the statistical model requires that homogeneous input data for rainfall and flows are sufficiently long for both calibration and validation exercises. For catchments with significant artificial influences (e.g. abstractions/discharges), it is essential that naturalised flow series are used for calibrations/validations. It is also important that calibration periods contain a wide range of climatic conditions for optimal results when reconstructing flows outside of the calibration period. Extensions further back to 1800 have been developed for a smaller number of catchments (Jones et al. 2006a).

Reconstruction of flows requires both homogeneous series of areal rainfall and monthly estimates of catchment-average actual evaporation – average values of the latter (which are unvarying from year to year) were derived by Wright (1978) based on simple water balance assumptions. The use of the same 12 monthly estimates of actual evaporation was argued by Wright (1978) to produce more reliable estimates of monthly flows and the resulting validation statistics bear this out (see, for example, Jones et al. 2006a). It also saves considerable effort in developing long series of potential evapotranspiration (PET) for each catchment.

Figure F.2 shows the reconstructions of flows for the 1907–1911 period compared to observations taken at the time (Strahan et al. 1916). With future climate change, it is unlikely that the assumption of constant actual evaporation will hold into the future but it has been shown to be adequate for the validation periods used in the 20th century. The goodness of fits of the results also implies that changes in land use across the 15 catchments have had a negligible effect on long-term flow statistics.

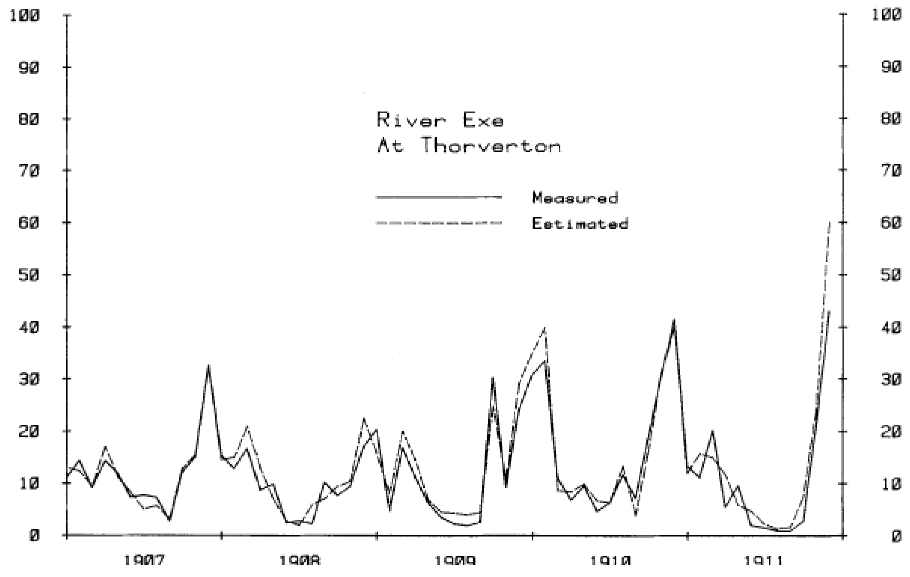

Figure F.2 Reconstructed and measured river flow on the River Exe, 1907–1911

Extensions with neighbouring catchments

The 15 catchments where reconstructions have been developed can be used with regression to provide extensions for neighbouring catchments. Care should be taken in the choice of which of the 15 to use, selecting not just the nearest or just one, but bearing in mind the geology of the catchment particularly with respect to the contribution from groundwater to surface flow. Previous work on changes in monthly and seasonal flow from the 1961–1990 average has shown that the Base Flow Index (BFI) and seasonal climate data provide the best basis for selecting donor catchments rather than distance (Wade and Vidal 2007).

Extensions with neighbouring catchments could be developed directly with the reconstructed flow series, but the areal rainfall series could also be used together with the rainfall–runoff model that works best for the catchment where extensions are needed.

Extensions to the daily timescale

Almost all water companies have complex models of their river and water resources systems which have been calibrated with observational values of rainfall, river flow and other series. These are generally run at the daily timescale. In order to take advantage of the long reconstructions of monthly flows, the earlier ‘severe’ droughts project (Jones et al. 2006a, Wade et al. 2006) used regression and a re-sampling technique to derive all the necessary daily input data to drive two resource models (one for the Anglian Region and another in the Lake District).

In these studies, monthly historic observed data were used with regression analysis to derive all the necessary monthly timescale inputs. The re-sampling technique then selected daily sequences appropriate to the estimated monthly average flows from the measured data.

This approach would be inadequate for flood-related studies, but is very suitable for water resources studies where low flows are of primary importance and particularly for lowland pumped storage schemes. The resource model can then be used with 150–200 years of reconstructed flow sequences to determine how recent observed droughts compare, with respect to measures such as levels of service with recent demand levels, to earlier droughts. Jones et al. (2006a) provide a step-by-step guide of the process to develop the necessary input data for a resource model.

Other climate variables

The only other potential variable that might be needed would be air temperature. For anywhere in England and Wales, the Central England temperature (CET) developed by Manley (1974) and updated in Parker et al. (1992) can be used again using the differences in temperature measured locally and that from CET (which extends back to 1659–1772 on monthly/daily timescales). Local temperatures can be extracted from the 5 × 5 km gridded sources discussed earlier (Perry and Hollis 2005a, Perry and Hollis 2005b, Perry 2006). Examples of the approach are given in Jones et al. (2006a) and Wade et al. (2006).

Step-by-step guide to extending hydrological data

The step-by-step guide given below has been produced based on the available data and methods described in the previous sections. Two methods that could be used for extending hydrological data series using the reconstructed data series and undertaking water resources modelling are described.

- **Method 1: River flow reconstruction from climate time series.** Where hydrological models are already available, it may be desirable to use these for producing simulated river flows and use them as input for water resources modelling. Where hydrological models are not readily available, new rainfall–runoff models could be set up using, for example, the statistical rainfall–runoff model used by Jones (Wright 1978) or other models such as CatchMod. However, this will require model calibration/validation which must pay particular attention to both the model fit for low flows and also model behaviour during extended dry periods. Developing such models for complex catchments affected by artificial influences can be labour-intensive and may only be warranted in systems shown to be vulnerable to extended droughts.
- **Method 2: River flow reconstructions from other river flow series**. A simpler approach is to develop riverflows series for use in water resources models directly from Jones' monthly river flow reconstruction records using regression methods. Riverflows from the nearest gauge with similar hydrological and hydrogeological settings are used along with factors or regressions to hindcast monthly flow records.

Both methods may require conversion from the monthly to daily timescale for use in water resources models. However, Wade et al. (2006) showed that simple monthly water resources models can mimic system behaviour and use of these models may be favourable for drought sensitivity or vulnerability analysis as opposed to the more labour intensive route of statistical re-sampling methods to derive daily data (see above).

The two methods are described step-by-step below.

Method 1: River flow reconstruction from climate time series

Method 1 assumes the use of reconstructed climate series (areal rainfall and evaporation) for the 15 catchments listed in Table F.1 and rainfall–runoff models. The method involves the following steps:

1. **Identify the nearest donor catchment with similar climatic conditions from Table F.1.** Areal rainfall records can be checked against the donor site using cumulative mass plots and double mass plots for the overlapping period with a view to developing regressions. BFI is an appropriate indicator of catchment similarity along with comparison of catchment climate data.
2. **Calculate monthly rainfall back in time based on regression relationship (or anomaly approach) between existing and donor catchment areal rainfall.** The development of reliable regressions requires a fairly large overlap between data series but, as most existing rainfall–runoff models cover the period from around 1920–2007, this includes a sufficiently wide range of climatic conditions to provide reliable relationships. An alternative method to using a set of monthly flow regressions (as described above) is using monthly factors that describe

the anomalies or deviations away from average rainfall (e.g. 1961–1990). This could potentially provide more accurate hindcasting in situations where the overall monthly correlations and regressions are weak. An appropriate assessment of goodness of fit is required to demonstrate the validity of which ever method is used.

3. **Select modelling approach (i) conceptual (monthly or daily) or (ii) statistical (monthly or daily with flow re-sampling) and prepare rainfall and PET series.**

    a. **Produce rainfall time series.** Depending on the overall aims and objectives of individual projects, conceptual or statistical models may be used. A range of conceptual models exist from daily rainfall–runoff models to simple monthly recharge models (e.g. Bloomfield et al. 2003, UKWIR 1997, Jones et al. 2006a, Moore et al. 2007, Wade and Vidal 2007).

    If a daily model is selected, convert monthly rainfall to the daily timescale using a re-sampling technique. Daily rainfall sequences are selected from either the donor record or existing record by identifying the month with the closest total rainfall and taking the daily values for this month. A daily time series is then constructed which uses daily values from different months and years. A simpler method would be to do the re-sampling based on seasonal or annual rather than monthly totals. Particular care must be taken using such techniques, as the re-sampling procedure may have a large impact on results, introducing bias (e.g. if the same daily pattern was selected repeatedly) and additional uncertainties. With a sufficient number of years, repeated re-sampling of the same data is unlikely.

    b. **Produce monthly potential evaporation time series.** Monthly potential evaporation has not previously been extended back in time due to very limited data availability; average monthly long-term average (LTA) values have been used instead which has been shown to be adequate for the 19th and 20th century. Alternatively potential evapotranspiration can be calculated from air temperature using different methods, the most commonly used being the Oudin formula or Penman equation. Monthly temperature data before 1914 are available from the Met Office at Southampton, Oxford, Bradford, Sheffield and Ross-on-Wye and the use of the widely researched CET record is appropriate for most applications (see above).

4. **Use reconstructed rainfall and monthly evaporation in rainfall–runoff models for producing modelled river flows.** Extend input data series for existing (or new rainfall-runoff models) in order to produce river flow series. Calibration and validation will be necessary if new rainfall–runoff models need to be developed. The modelled river flows are then naturalised for use in water resources modelling.

    A monthly conceptual or statistical model may be appropriate for many applications, e.g. estimating changes in recharge. As in Jones et al. (2006a), a re-sampling technique can be used to estimate daily flows for the purposes of water resources modelling. In some cases, such as upland reservoirs or natural lakes, the daily re-sampling procedure may have a significant impact on results in a similar way to rainfall re-sampling procedures.

5. **Use modelled monthly or daily river flows in water resources modelling (DO assessments and levels of service).** Reconstructed

naturalised monthly or daily flow series are prepared from the rainfall–runoff model results and used as input for water resources models.

Method 2: River flow constructions from other river flow series

Method 2 makes direct use of the reconstructed river flow series for the 15 catchments in Table F.1 and includes the following steps:

1. **Identify the nearest donor catchment with similar hydrological properties from Table F.1.** Simple checks on soil properties and base flow component can initially be performed using the National Soil Resources Institute website (LandIS website: http://www.landis.org.uk) and the Hydrometric Register and Statistics 1996–2000 (CEH and BGS 2003). Comparisons of flow duration curves and cumulative flows for existing records and the donor site for the overlapping time period are also useful for establishing similarities.
2. **Calculate monthly river flows back in time based on regression relationship (or anomaly approach) between existing and donor river flows.** The development of reliable regressions (based on the full log-transformed flow series, monthly series or flow duration curves) requires a fairly large overlap between data series but, as most existing water resources models cover the period from around 1920–2007, this includes a sufficiently wide range of hydrological conditions to provide reliable relationships. An alternative to using regression is to develop monthly factors or anomalies expressed as a percentage change, standard deviation or z-score deviation from the 1961–1990 average. This may be more reliable for hindcasting in situations where the overall flow correlations are weak**.**
3. **Convert monthly flows to the daily timescale using re-sampling if daily flows are required for water resources modelling.** Daily flow sequences are selected from either the donor record or existing record by identifying the month with the closest total river flow and picking the daily values for the month. A daily time series is then constructed which uses daily values from different months and years. A simpler method would be to do the re-sampling based on seasonal or annual rather than monthly totals, which could potentially produce a more consistent flow records. Care needs to be taken as noted in point 3a above.
4. **Use reconstructed monthly or daily river flows in water resources modelling (DO assessments and levels of service).** Reconstructed naturalised monthly or daily flow series are prepared and used as input for water resources models.

Appendix G Guidelines for conducting drought workshops

Background

This appendix provides guidance and suggests things to consider when developing exercises for workshops aimed at testing the resilience of water resources systems to severe drought. It does not cover how to go about choosing a catchment or a drought scenario or how to develop the water resources model, but considers solely the workshop design.

The workshop exercise described below is based on a strategy game approach. Strategy games have been applied in many different situations (e.g. military strategy, corporate strategic planning and forecasting, public policy and disaster preparedness). They provide a way to integrate intangible and non-quantifiable factors (political, societal and economic) into strategic planning processes. They can be used to think through crisis management and assess the performance of different strategies in advance.

The basic requirements for a game are a scenario, a set of roles and some rules. The game is managed by a facilitator with assistance from a core team. Frequent communication between the facilitator and the core team throughout the exercise allows changes to be made to the scenario as it is being played. The scenarios can vary in the level of detail presented; they could be very abstract or very precise. The roles can be anything from completely abstract to highly realistic, or they could be developed as the game is played. The rules can be rigid or unconstrained.

The aim of such an exercise is to investigate a plausible, low probability but potentially serious consequence of a drought scenario of an extended period (3+ years). This same exercise could also be undertaken through interviews with individuals from the organisations involved – typically the Environment Agency, Defra and the water companies. In a workshop setting, however, you have the added advantage that you can hear and respond to different views and get an immediate reaction to an intervention. It is through these interactions that it is possible to uncover plausible reactions and interventions in response to the drought scenario.

This game approach is, of course, a simplification of reality and so trying to recreate external influences such as media pressure or special interest groups demands (though potentially significant) may be outside the scope of such an exercise. It would typically be considered sufficient, for a one day workshop, to simply get a response to the hydrological and water resources model data as they emerge and rely on the experience of the participants for the meaning of this for the work of the Environment Agency and Defra, and the implications for the public. Inevitably there will be a balance between the advantages of a very detailed exercise and the resources available to undertake it.

Ideally it would be beneficial to have representatives from the main organisations involved in drought management in the UK including the water companies, regional and national Environment Agency, and Defra. Other voices could also be brought in (e.g. media, public, special interest groups) to include other important influences on decision-making – either having live representatives of these actual groups, people role-playing them or other ways (e.g. mock-ups of newspaper reports, public petitions, interviews with someone role playing a journalist, etc.).

When resources (skills, money, time, etc.) are more constrained, there has to be a reflection on the value of such an exercise and how testing of the drought system and plans can be achieved most effectively. The voices of Defra and the national Environment Agency should be represented, but this could be achieved by a water company staff member in role. It is recommended that a representative of the regional Environment Agency is present if at all possible.

Preparations before the exercise

The main effort before the exercise is in preparing the simulation model and ensuring that, as well as being a sufficiently realistic representation of the system, that it is easy for participants to understand and interact with.

Preparation will typically include:

- data collation (climate and hydrology) and water resources model review;
- analysis of available climate and hydrological data for identification of drought periods and assessment of water resources vulnerability to drought;
- development of new water resources modelling tools or modifications to existing tools to include an appropriate interface for interactive use in a workshop setting;
- extension of available climate and or river flow time series back in time (see Appendix F);
- drought scenario selection based on analysis and water resources modelling;
- review of water company drought plans and identification of drought measures previously used for managing drought;
- further data collation on environmental impacts.

Agenda

A week in advance of the day of the workshop, a brief agenda should be sent out to the participants. This should map out the beginning and ending times, and provide a sketch of what might be happening. It is important not to give away too much information on the nature of the scenarios as the ‘surprise’ factor is important if you want to get a plausible response to the data as they emerge.

Figure G.1 shows an example agenda.

Figure G.1 Example agenda for long droughts exercise workshop

9.30	Welcome and introductions
9.40	Overall purpose of the meeting To test out current drought planning in a scenario of a long drought To plan how to address needs arising
9.45	Introduction to the scenario and the rules of the game
10.00	Scenario 1
12.15	Debrief 1
13.00	LUNCH
13.15	Scenario 2
15.15	Tea/Coffee
15.30	Debrief 2
16.00	Reflection on the day

Recording interventions

As the workshop depends a lot on interactions in the moment, some thought has to be given into how these should be recorded in a way that does not require too much time-consuming transcription afterwards.

Clearly how this is done is up to the people involved. The list of devices used in this project is given below:

- a spreadsheet model (or other type model) projected onto a large screen and visible to all participants;
- a template to record interventions;
- a timeline to provide a visual representation of the interventions;
- a template for the annual reviews;
- facilitated scenario debriefs;
- facilitated overviews of the day.

These devices are described in more detail below.

The example template shown in Figure G.2 captures how particular decisions are made during the game. It is intended to be a quick way to pick up the key points in a way that does not interrupt the flow of the discussion and the unfurling of the scenario significantly. Such a template can be used to provide a checklist of questions to be loosely followed.

Figure G.2 Example template for recording interventions

Intervention:	
Reasons stated for taking action at this point:	
Other options considered:	
What influenced the decision (information, organisations, events) either positively or negatively:	
Intended (hoped for) consequences of the action:	
Possible negative consequences of action:	
Any other concerns:	

Timeline of interventions

A timeline can be created on the wall, year by year, as a way to represent decisions and actions as they emerge from the water company, Defra and the Environment Agency. This can be constructed in 12-month blocks with each year represented on flip chart paper (one sheet is 12 months). Each annual sheet is added to the earlier sheet to create the whole timeline.

This visual representation is then available for the annual review process.

Figure G.3 shows an example timeline.

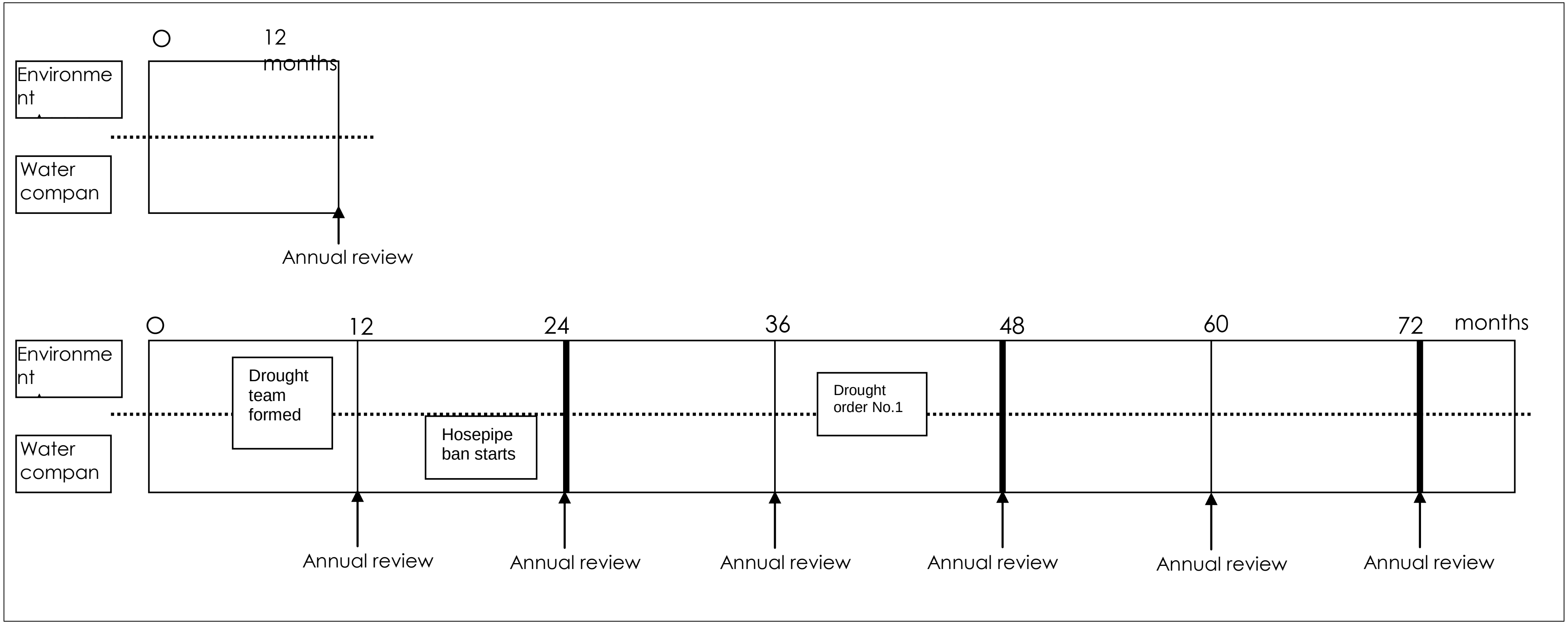

Figure G.3 Example of emerging timeline of actions captured on a flip chart

Template for annual reviews

Annual templates completed by a member of the facilitation team can form the structure of the report by the water company to Defra and the Environment Agency. Figure G.4 shows an example template.

After the water company has reported their concerns and actions, the Environment Agency and Defra have the opportunity to give their own reflections on the year and ask the water company challenging questions.

Figure G.4 Example template for annual review

WIMBLEBALL: SCENARIO ONE	
Year 1 Annual review	
Summary of the hydrological data Consider questions such as: How unusual a year was this? What made it unusual? What concerned you about the hydrological data as it unfurled?	
Summary of drought planning activities Consider questions such as: What drought actions did you take in response to this data and why? Did you have all the options you needed available to you? What was missing?	
Communication activities (internal and external) How effectively were you able to communicate: • internally? • externally with other organisations? • externally with customers?	
What do you believe to be the consequences of your drought planning decisions for : • for the company (financially and for its reputation)? • the environment? • for customers?	
EVALUATION Mark on the spectrum below how well you think performed this year. Questions to then consider include, for example:	

Why did you not place your cross at zero (what did you do well)

Why did you not put your cross at 10 (what could you have done better).

What could you have done differently to move closer to 10?

What support would you need to move closer to 10?

Facilitated scenario debrief

This debrief happens at the end of each scenario. Many of the questions will emerge through the exercise, although some can be anticipated.

The scenario debrief is an opportunity to reflect on:

- what happened during the game;
- what was surprising or interesting of relevance to drought management planning activities within the water company and the consequence of this for the Environment Agency and Defra.

The aim is to stand back a little from detailed content questions – though there may be a need for some for the sake of clarification – and ask questions for reflection on the action taken. Examples include:

- Looking at your performance targets over the four years, how well do you think you coped with this drought?
- What could you have done to improve your performance? What stopped you being more successful?
- Are you prepared for such a drought? What aspect of it concerns you most?

During the debrief, a member of the facilitation team takes notes on what was said. These notes can then be verified with the participants.

Overview of the day

The aim of this final section is to find out what participants consider to be the most interesting or pressing issues to have emerged from playing the game.

This is an opportunity to:

- put the scenarios in the context of existing management plans;
- ask whether these plans are sufficient or if changes need to be made to make them more efficient in the event of a long drought;
- discuss the strengths and weaknesses of the scenario game and how plausibly it represents the real world.

Things to consider during the exercise

Depending on who is present at the workshop and how much they know about the catchment of interest, it may be worth spending a few minutes describing the main features of the catchment to set the scene in order to get the water company and Environment Agency perspective on this.

It is difficult to anticipate in advance how long people will want to spend discussing changes in the hydrological data and the facilitator has to create a balance between allowing things to emerge and keeping on track. After explaining the basic rules it is recommended to allow the first year to be played through quite slowly and use it as an exercise in learning by doing.

There is a choice about who fills in the templates and the intervention notes (written on ‘post-it’ notes) that go on the timeline. It may save time if one of the core team fills it in, but getting the participants to fill it in means that you get it in their words rather than interpreting it into your own. There is a balance between accurately and concisely capturing what the participants are saying and not writing so unclearly that you are unable to read it later.

As well as the focus on the content of the scenarios, there should be a wider discussion of the approach. This enables participants to discuss the plausibility of the exercise and how easy is it to look at the future like this.

Wrapping up after the exercise

After the exercise the templates, timelines and other notes need to be written up and key themes identified and presented back to the participants for their feedback. This is an opportunity to verify what was said and to ask if they have had any further thoughts – either after the workshop or as a result of reading the report. The findings from the exercise can then be presented at a feedback workshop to highlight key issues or areas for change arising from the exercise.

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