Impacts of long droughts on water resources – draft final

Science Report – SC070079/SR

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Author(s):
Birgitte von Christierson
Jamie Hannaford
Kate Lonsdale
Simon Parry
Jemima Rance
Steven Wade
Phil Jones

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Research Contractor:
HR Wallingford Ltd.
Howbery Park
Wallingford
Oxon, OX10 8BA
HR Wallingford Report Number SR 695

Environment Agency's Project Manager:
Stuart Allen

Collaborator(s):
CEH
UKCIP
CRU University of East Anglia

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Steve Killeen

Head of Science

Executive summary

The water resources and drought management plans for the United Kingdom (UK) 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 2003/4 to 2006 and the prospects of a third dry winter in 2006/7 raised the issue 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 (Vidal and Wade, 2008).

The purpose of this research project was to assist the Environment Agency in testing the current drought management framework against severe long droughts. Two different types of systems: Wimbleball in the River Exe catchment in the South West of England and Grafham located in the Ouse catchment in Anglian Region were considered. 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 1868-71, 1886-8 and 1895-96 (Wimbleball) and 1801-04, 1807-08 and 1815-17 (Grafham). Participants responded to hydrological situation reports, reservoir levels and actions of other stakeholders to prompt implementation of drought management measures.

Generally, 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 that further drought planning guidance is needed in the following areas:

- **Drought planning guidance should emphasize 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 early demand restrictions including enhanced communication, hosepipe bans and non-essential use bans at various stages of drought even when different triggers were hit, although these measures were included in the water company 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 measures and actions 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 of these were well-established practice.

- **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 made aware 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). A further need for joint EA/Defra guidance to clarify the difference between drought permits and drought orders was identified.

- **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 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 range of normal behaviour to identify unusual reservoir behaviour and present these in their 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, for example outage during periods of drought.

- **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 amongst both the water companies and within the Environment Agency.

A number of areas for further research were also identified based on the workshops.

- Further research into improved flow forecasting methods including use of medium range weather predictions is recommended.

- Further investigation on how to present and communicate very low probability and high consequence drought events to the public, including the measures needed to maintain water supply, is necessary.

- Research is needed on identifying barriers within the water companies to introducing demand-supply measures in a timely manner.

- Water companies could benefit from further research on development and use of multi-variate triggers.

- Further research is needed with respect to environmental needs during severe droughts and the environmental and other consequences of drought.

- Research is needed into the modes of failure for different types of water resource systems.

- Further examination of the link between Water Resource Planning and Drought Planning, including the use of 'headroom' for managing drought is required.

- Testing of the drought management planning and management system for groundwater dominated water resource zones should be undertaken.

- More research should be undertaken on the impacts of climate change on autumn flows.

- Research on the practical use of drought indices for monitoring drought development should be carried out.

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Contents

1. Introduction

1.1 Background

The water resources and drought management plans for the United Kingdom (UK) 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 the South East of England in 2003/4-06 and prospects of a third dry winter in 2006/7 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.

The ‘Severe Droughts’ science project undertaken for the Environment Agency in 2006 by a consortium consisting of Climatic Research Unit (CRU), CEH and HR Wallingford (Marsh and Cole, 2006; Jones et al., 2006; 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 the North West the impacts on water supply were less severe but there were potential environmental impacts that may conflict with the Habitats Directive and Water Framework Directive objectives. The research showed that there were major droughts in the 19th century that were more severe than the ‘design’ droughts that are 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 than 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.

Water companies in England are required to consider a range of droughts in Water Resources Plans and Drought Plans, both of which are statutory documents shared with interested stakeholders. As part of the Draft Water Resources Plans for Periodic Review in 2009 (PR09) several companies considered the potential impacts of a third dry winter in 2006 following dry winters in 2004/5 and 2005/06, 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 and it is clear that this provides a good representation of short droughts, such as 1921/22, 1933/34, 1975/76 and 1995/96. 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 but have focused on the need to maintain supplies rather than temporarily restrict demands during these periods.

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 the Defra Water Resources Policy Unit due to its relevance to EU policy initiatives such as (a) the European Communication on water scarcity and droughts that addresses how droughts will be managed in the context of the Water Framework Directive (WFD) and (b) the proposed European Drought Observatory.

1.2 Objectives and purpose of this document

The overarching aim of this research project was to examine the impacts of long droughts on water supply and the environment and to 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 19^{th} and 20^{th} century.

The project has been 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. The first chapters of the report provide an overview of the current drought management framework including legislation, policy, guidance and practical experiences from more recent droughts. The report describes the selection of two catchments/water supply systems which were identified from discussions with the Environment Agency in the initial phases of the project and have been used for testing the drought management measures in Stage 2.

The report also looks at definitions and methods for identifying and characterising "long droughts" building on findings from the previous severe droughts project (Marsh and Cole, 2006; Jones et al., 2006; Wade et al., 2006) and considers more recent research on the use of drought indicators. An analysis of historical data, including anecdotal impacts of drought on the environment, used for selecting suitable drought periods for the workshops is also described. The final chapters describe the two drought workshops, main findings and recommendations for potential improvements to the drought planning and management system.

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:

- '*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.

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. As such, there is no single definition of drought but a series of related concepts relevant to different disciplines, economic sectors and drought durations (see Wilhite and Glantz, 1985, for an original description of drought definitions).

For the purposes of this study the following 'water resources drought' definition has been adopted:

"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 resource systems as illustrated in the previous 'Severe Droughts Science' project. Further definitions of 'long' droughts and drought indicators are discussed in Chapter 4. A number of other definitions used to describe drought is included in Text Box 1.

1.4 Structure of the report

The report is structured as follows:

- Chapter 2 Overview of the existing drought management framework including legislation, policy, drought plans, guidance and past experiences of drought management.
- Chapter 3 Selection of two case studies including overview of available data, existing models, development of simple spreadsheet models for the workshops.
- Chapter 4 Drought definitions, characterisation and identification including various drought metrics. A provisional drought selection for the two case studies based on climate and hydrological data is also included.
- Chapter 5 Testing of drought management system through interactive workshops with the Environment Agency, water companies and Defra, including resilience of the current drought system to cope with long droughts and evaluation of drought measures.
- Chapter 6 Recommendations for improvements to the current drought management framework including additional needs for guidelines and new research.

Text Box 1 Drought Definitions

The report adopts the following definitions to describe drought and water resource systems.

- 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.
- Levels 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 the Consumer Council for Water (CCW). 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.
- 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 resource 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 issues in England and some water resources issues in Wales. Most water resource issues in Wales including drought orders are handled by the Welsh Assembly Government. There are three main regulators who work with Defra and the Welsh Assembly:

- The Environment Agency: the management of water resources and protection of the environment. The Environment Agency will monitor water companies 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 main legislation controlling water abstraction in England and Wales are the Water Resources Act (1991) and the Water Act (2003). The duties of all water companies are detailed in the Water Industry Act 1991 and Water Act 2003 including their obligation to produce a drought plan. Water companies' powers to restrict the use of water use are set out in the Water Industry Act 1991. The Water Act of 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 and the Environment Agency will continue to encourage water companies to make the full plans available to the public.

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. 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 by the National Assembly for Wales. These are described in further detail in section 2.2.3.

The management of water resources in the UK is influenced by the Water Framework Directive (WFD). It was introduced in 2000 to consolidate existing legislation into one policy and consequently integrate and improve the management of water resources in Europe. The Directive provides a further framework in addition to national legislation to protect the environment by planning to achieve good ecological status for all water bodies. It is the only EU legislation that deals with the management of droughts. The Habitats Directive is included in this legislation and could affect drought management since it influences abstractions. Water scarcity must be avoided in those areas designated as 'Natura 2000' sites under this directive, which has implications for the way in which water companies prepare for a drought.

Drought plans should be consistent with Water Company Water Resource Plans (WRPs) that make assumptions concerning the frequency of drought management measures. They should also have regard to the requirements of the Habitats Directive and ensure that drought measures do not impact adversely on designated European sites. In future, drought planning will need to be more closely integrated with River Basin Management Plans (RBMPs) that are required under the Water Framework Directive. 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.

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

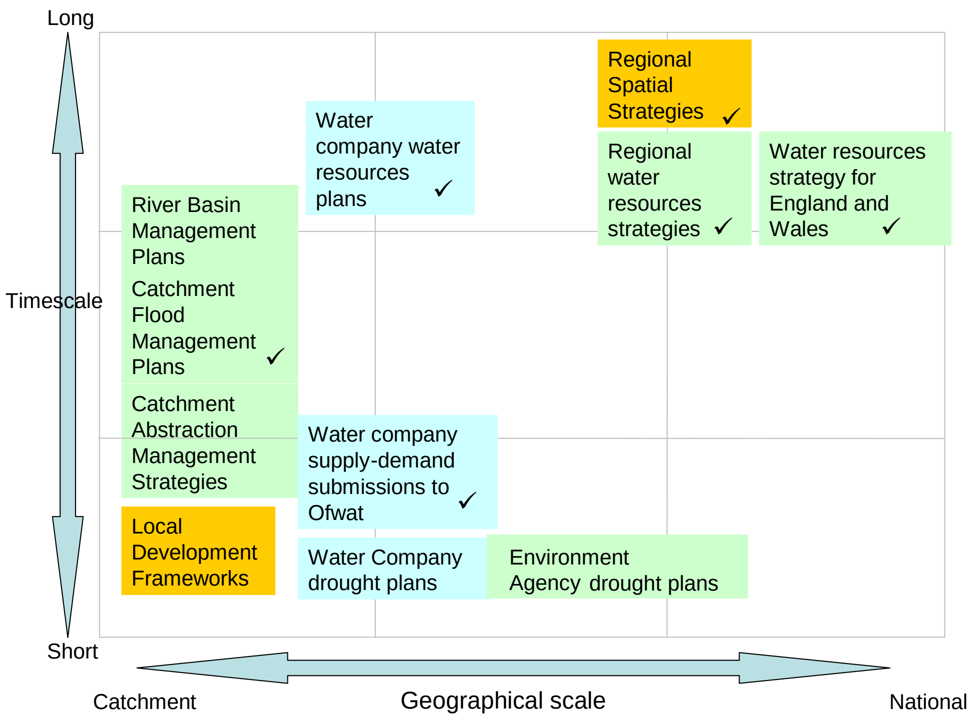


Figure 2.1 Planning activities relevant to water resources and drought management (adapted from Environment Agency, 2001) including those that include a consideration of climate change (✓)

2.2 Drought plans

Water companies have a statutory duty under the Water Act 2003 to produce drought plans that are submitted to Government Ministers. Drought planning guidance produced by the Environment Agency (Environment Agency, 2005) outlines the issues that the plans should consider. Furthermore the plans should be produced in accordance with the requirements of the Strategic Environmental Assessment (SEA) Directive, 2004. The Environment Agency also prepares its own drought plans that describe the actions that the Environment Agency will take to detect and manage drought.

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, whilst minimising 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 allows for three mechanisms for dealing with the situations: drought permits, drought orders and emergency drought orders (described in section 2.2.3).

Drought plans are about managing climate variability and do not currently consider climate change. The plans are updated every three years with the latest published in 2007/08 and involve short term actions rather than influencing long term investment strategy. Therefore, the plans can evolve alongside climate change or long multi-seasonal droughts and actions can be adapted to more frequent drought conditions.

The key features of the 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 Environment Agency and water company drought plans are described in further detail in section 2.2.1 and 2.2.2 respectively.

2.2.1 Environment Agency drought plans

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

The plans describe the actions the Environment Agency will take to reduce the effects of the drought on water users. They also detail the management procedures as well as the Environment Agency’s role in issuing drought order and permits and dealing with any potential applications that may come in. The Environment Agency will review their drought plans, which account for potential climate change, every three years.

The requirement for regional drought plans was identified due to close involvement in the water company drought plans and as a result of the findings of an internal audit of drought management. The key actions to be taken during a drought are identified in the plan along with details of how a drought status will be recognised using environmental data from around the catchments. A principal aim of the plan is to present a structured framework for drought management whilst maintaining the level of flexibility required to respond to different types of droughts.

Drought management teams have been established at both area and regional level and include representatives from all relevant functions to ensure that drought management is conducted in a co-ordinated manner. Meetings will normally be held at least once per month during a drought event but the frequency may vary depending on the nature of the event. Representatives of the regional drought management team will undertake regular liaison meetings with water companies to ensure that drought measures are coordinated and opportunities for putting across joint messages to the public are maximised.

The regional plans set out:

- Drought monitoring arrangements including appropriate hydrological and environmental triggers;
- Drought management actions (see Table 2.1 from Thames Region's drought plan).

Table 2.1 Actions undertaken during each water resource 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, English Nature, British Waterways, CPRE, NFU, 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 been submitting drought plans to the Environment Agency, however now the process is statutory and they need to be submitted to the Secretary of State. 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 (EA, 2005). They are also required to avoid any detriment to the environment where possible. The key issues that have to 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 with a variety of parties, including the Secretary of State/NAW, the Environment Agency, Ofwat and licensed water suppliers, before the plan is prepared. Some of the main requirements are given in Table 2.2:

Table 2.2 Main requirements of water company drought plans (Adapted from EA, 2005)

Requirement	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. This corresponds to the severity of the drought, for example at what stage drought management should be implemented once a trigger is reached.
A number of different possible scenarios	These include different ranges of dry summers and winters as well as multi-season droughts. This will improve its resilience to a number of possible drought situations and therefore improve management planning. The water company must give reasons for choosing these scenarios.
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 Habitats Regulations Act. Environmental factors, which could be affected by any drought measures as detailed 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 Consumer Council for Water (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.
Communication strategy	How the company will provide information to its customers through its communication strategy, for example when and in what way the information will be provided during a drought.
Actions to be taken following the drought	These must be addressed and if there are any reviews needed of the plan then it should be updated.

Potential sites for drought orders and drought permits should also be considered; otherwise it is unlikely that they will be supported by the Environment Agency. 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.

2.2.3 Drought orders and permits

Drought orders and permits can be granted under the Water Resources Act 1991, 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 authorised in England by the Secretary of State or in Wales the National Assembly for Wales (NAW). Further details are given in Table 2.3. Guidance and instructions on applying for drought permits and orders are provided by Defra (Defra 2005). Drought orders can be granted to water companies to reduce demand and increase supplies and to 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 need to have made an effort in implementing 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. It does however 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 the 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 (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 to the EA, Defra and English nature and submission of environmental reports along with the application.

Table 2.3 Differences between drought permits, drought orders and emergency drought orders (adapted from Defra, 2005).

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	▪ Granted in England by the Secretary of State and in Wales by the National Assembly for Wales ▪ 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 by the National Assembly for Wales ▪ Duration: three months and can be extended to five months

2.3 Experiences from recent droughts

The existing drought framework was last tested during the multi-seasonal drought in 2004-06 in the South-East of England. The drought was one of the worst in the last 100 years and based on drought indicators assessed to be an extreme albeit not exceptional drought (Environment Agency 2008). The drought of 1976 still remains the most intense in the past 50 years; however the 2004-2006 drought endured for longer than both the 1989-90 and 1997-98 events.

The summary report of the 2004-06 drought produced by the Environment Agency in August 2008 and hydrological prospect reports published by the Environment Agency during the drought (Environment Agency 2006, 2006a and 2006b) indicates that 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 drought plans, drought groups were formed and convened regularly to appraise the situation and once critical thresholds were reached the groups were in close contact with the water companies, other abstractors and Defra keeping the key 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. 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 and weekly reporting was published on the internet (water companies worked closely with the Environment Agency in publicity campaigns);
- A new drought permit was issued to Sutton and East Surrey and two drought permits were extended;
- Formal restrictions on 600 spray irrigation licences were introduced in collaboration with the farmers;
- A number of actions for the water companies was recommended.

The water companies largely followed the recommendations published by 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, Mid-Kent 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 Utilities Ltd, 2006);
- 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) were extended;
- Leakage control was improved although complaints from gardeners 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 to have reduced customers' demand for water by 5-15% and supply was 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. Some discontent with insufficient leakage control was raised by a number of groups such as gardeners which felt the impacts of non-essential use bans on their businesses were disproportionate.

The lessons learned during the drought of 2004-06 have led to a number of suggestions for improvements to the framework. The drought drew attention to the need for modernisation of the scope of hosepipe ban powers. The existing powers apply only to watering private gardens and washing private motor cars. There are however 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 is clear and unambiguous.

The two main changes currently under consideration are: modernisation of the hosepipe ban including non-essential use (Waterwise, 2006) and development of a water industry code of practice governing demand restrictions. A consultation document (October 2007) is available on the Defra website 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 the Defra 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 ends 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. There have not been shortages of public water supply over the last decade, despite the two notable drought periods in 2003 and 2004-06.

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

The main limitations in the current drought framework, particularly with regards to hosepipe bans and restrictions of non-essential use was identified by Waterwise in 2006 based on experiences from the 2004-06 event are outlined below.

- **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 2004/06.

- **Lack of flexibility for improvements in technology.** Restrictions apply to all irrigation systems although some are more water efficient than others.

- **Lack of concessions.** No concessions to elderly/disable 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 to be approved and implemented shortly. The draft Flood and Water Management Bill recently published includes provisions to enable the Secretary of State and Welsh Ministers to extend water company hosepipe ban powers, which will enable water companies to ban a wider range of discretionary uses of water. Under the new legislation uses of water not currently covered by the hosepipe ban, such as filling of private swimming pools and cleaning of 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 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 (such as hose pipes). Furthermore a requirement to publish a notice in at least two local newspapers and on the company's web-site 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 more resilient to drought stress now, there is the question of whether it would be able to cope with long drought conditions should they occur (Marsh et al., 2007). Whilst the drought plans consider multi-seasonal drought scenarios, these are based on more recent droughts (2004-06) or other historical droughts back to 1920 which may be less severe than those from the turn of the 19^{th} and 20^{th} 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 Anglian Region and Wimbleball in the South West were selected for this research study in order 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 resources 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 the previous Environment Agency research on Severe Droughts (Cole and March, 2006; Jones et al, 2006; Wade et al., 2006). Therefore this project case study builds directly upon the previous work with a new focus on drought management responses.

Similarly, Wimbleball was subject to a previous Environment Agency and Tyndall Centre 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 within the Exe river catchment, which has more than twice as much precipitation and runoff eight times higher than the Ouse (Table 3.1). Grafham has net storage volume of 55225 Ml, more than twice the size of Wimbleball Reservoir at 21230 Ml.

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

Table 3.1 Characteristics of the two case study areas (a) catchment water balance (b) flow reconstructions and (c) water resources models

(a)

	Water Balance (Marsh and Hannaford, 2008)			
Catchment	**Baseflow Index**	**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

(b) Synthetic flows available

River	**Flow gauge**	**Gauge No**	**Catchment area (km^2)**	**Max. elevation (m)**	**Q95 (m^3s^{-1})**	**Q10 (m^3s^{-1})**
Ely Ouse	Denver Complex (1865-2002) (1801-2002)	33035	3430	167	0	29
Exe	Thorverton (1865-2002)	45001	601	519	2	39

(b)

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, Exbridge pumped storage	Wimbleball (inc. Clatworthy and other sources) LancMod water resources model Miser water resource model Wimbleball spreadsheet model (developed for this study)

3.1 Anglian Water – Grafham

Grafham reservoir abstracts water from the River Ouse at Offord intake above a prescribed Minimum Residual Flow (MRF). The reservoir has limited natural inflow and relies on river abstraction throughout the year. The reservoir is mainly used for direct public water supply passing through Grafham Water Treatment Works (WTW).

A schematic of the system is shown in Figure 3.1 and key reservoir parameters including Minimum Residual Flow (MRF) and compensation flow are included in Table 3.2.

GRAFHAM SYSTEM SCHEMATIC (ADAPTED FROM AWS, 1997)

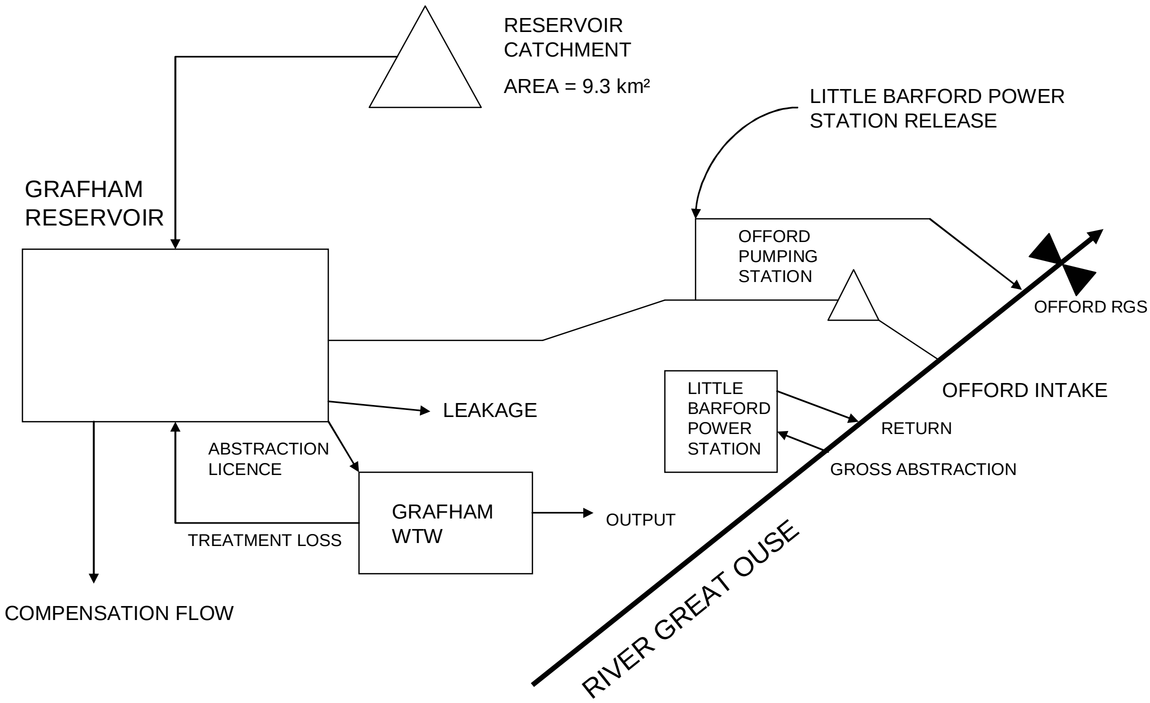


Figure 3.1 Schematic of the water resources system for Grafham

Table 3.2 Licence and prescribed flows for Grafham reservoir

Licences	Daily (Ml/day)	Annual (Ml)	Additional comments
Offord PS	485		Minimum Residual Flow = 136+0.25(Flow-136) Ml/d at Offord GS
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 which 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, the use of a regional or Water Resource Zone (WRZ) trigger is not possible in Anglian region. Restrictions on demand are therefore included as a trigger on 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 shown along with associated actions in Figure 3.2 and Table 3.3. 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 and trigger curves below

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

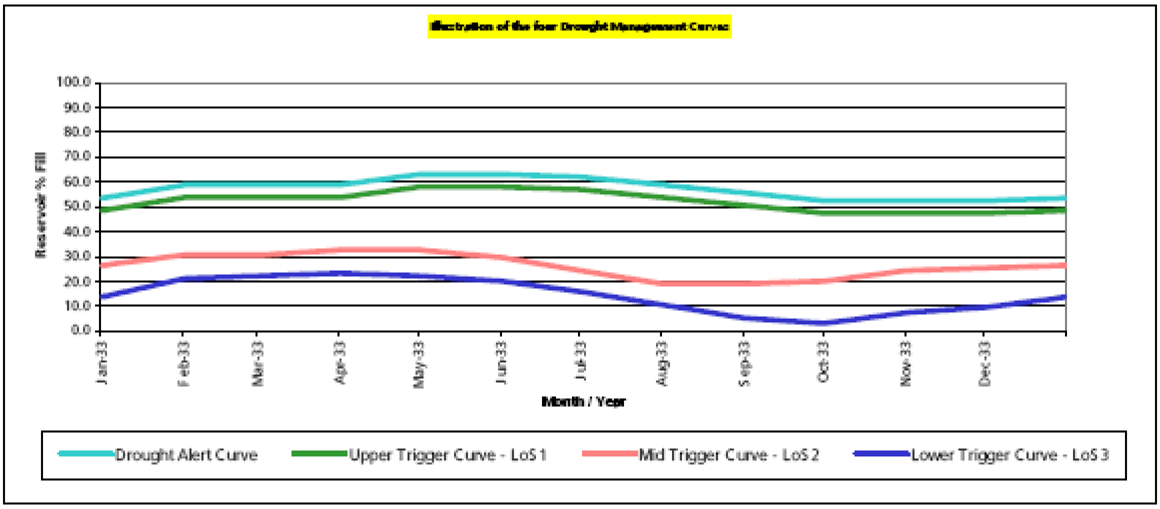


Figure 3.2 Example of drought trigger curves

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 to 2002 that were 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 to 2004 (Jones et al., 2006)

- Gauged river flow records for the period 1980-2002 for Denver Sluice and Offord from the National Water Archive[1].
- Reservoir, abstraction and demand characteristics suitable for detailed 'behavioural modelling' of the reservoir and/or water resources zone.

In addition to this information other hydrological data such as spring flows and groundwater levels were collated. Available anecdotal evidence of the impacts of historical droughts on the environment in Anglian region was also examined and is described in further detail in section 4.4.

Anglian Water were consulted directly to gather the latest thoughts on likely demand reductions during drought conditions and other information, which supports the drought plan. This information was mainly used for preparing to test the drought management system in a workshop setting described in Chapter 5.

3.1.3 Water resource modelling

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

Anglian Water uses their in-house OSAY model for water resource management and planning for Grafham. The OSAY model is a windows-based application, which calculates the water balance of the reservoir based on river flows, licence conditions, pump capacities, reservoir characteristics and target level of service. This kind of model is often described as a behavioural model. For 'No Restrictions' runs, it 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 it 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. The details of the OSAY model are described in Mott MacDonald (1997) and notes provided by the software developer (Clarke, pers. comm.).

Wade et al., (2006) developed a simpler spreadsheet model for Grafham 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. Due to the simplicity of the spreadsheet modelling tool and a need to make changes to the model to allow for drought management decisions to be considered interactively in workshops this model was selected for use in the study.

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 and general presentation of the results showing trigger curves and demand deficits. The original water resource spreadsheet model for Grafham is described in Appendix 2 of Part 3 of the Environment Agency, Severe Droughts Science Report (Wade et al., 2006) and 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 the appendix.

[1] Denver NWA record is patchy and incomplete – further data are needed from the EA to complete the record.

Groundwater modelling tools were also initially considered for the study in order to test the impact of drought conditions and drought management for both surface water and groundwater sources within the Grafham Water Resource Zone. However due to time pressures and the need to keep the modelling relatively simple for practical reasons for the workshops detailed groundwater modelling was not considered 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 for augmentation of 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.

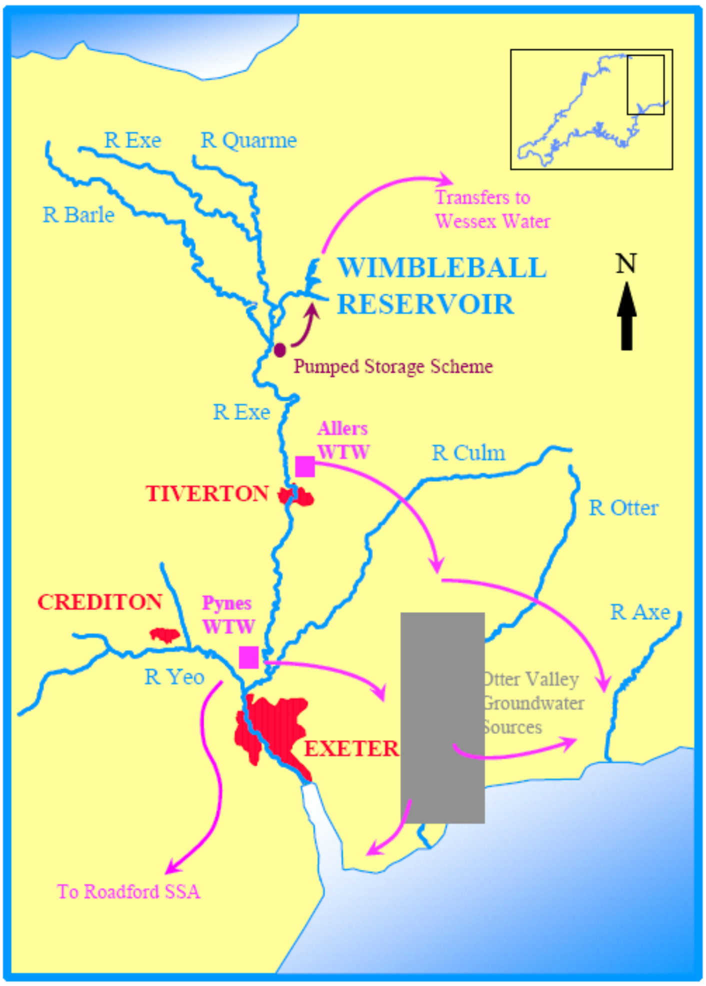


Figure 3.3 The Wimbleball Strategic Supply Area (South West Water, 2007)

Table 3.4 Licences and prescribed flows for Wimbleball reservoir

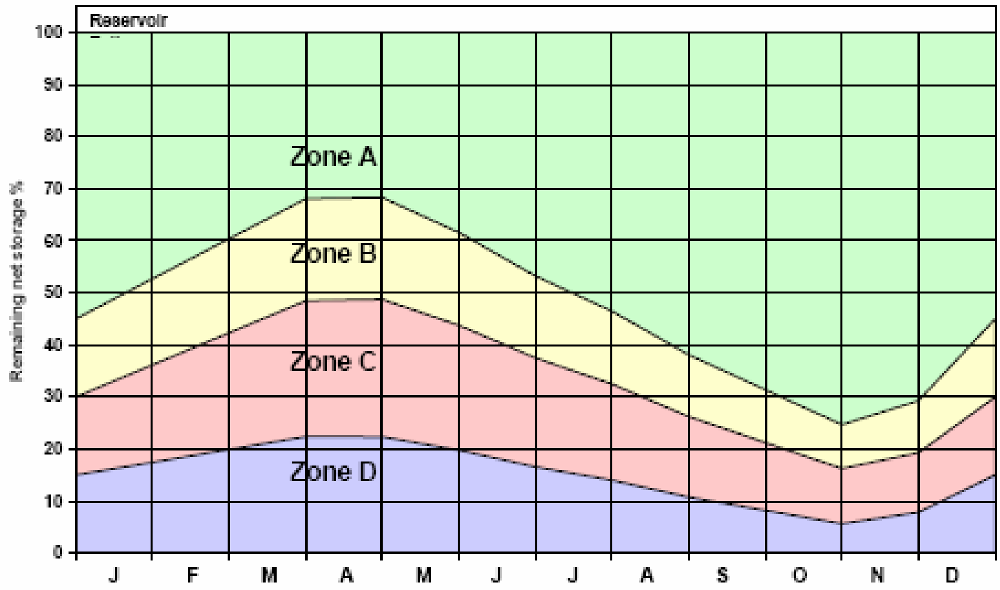
Licences	Daily (Ml/day)	Annual (Ml)	Additional comments
Wimbleball PS	150	13633 (Jan-Dec)	Abstraction between 1st Nov and 31st Mar only
			Prescribed flow = 1.16 m3/s, 50 % take
			Annual Fisheries bank = 900 Ml
			No abstractions for PS at the same time as making releases from Wimbleball
			Maximum abstraction rate of 135 Ml/d (operational contingencies)
Wimbleball release		12585	
River Exe at Northbridge Licence of Right (for Pynes WTW, Exeter)	24.457	8926.8	Licence of Right
River Exe at Northbridge (for Pynes WTW, Exeter)	42	14300	Prescribed flow = 3.16 m3/s at Thorverton GS (based on Thorverton natural flow)
River Exe at Bolham (for Allers WTW, Tiverton)	32	11564.5	When the natural flow in the R. Exe at Thorverton is 3.16 m3/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

Similarly to Anglian Water's drought plan South West Water's drought plan is based upon drought management curves for their three strategic supply areas. A slightly different terminology has however been used for describing the "trigger" curves. South West Water distinguishes between local and strategic reservoirs which have different storage zones related to Level of Service (LoS) 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 firstly 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 have been developed theoretically and then refined based on different historical droughts.

An illustration of the drought management curves including zones and associated actions is shown in Figure 3.4 and Figure 3.5. In terms of actions taken during different stages of a drought these seem to differ somewhat from those used by Anglian Water. With regards 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. No specific information on these drought orders has however 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

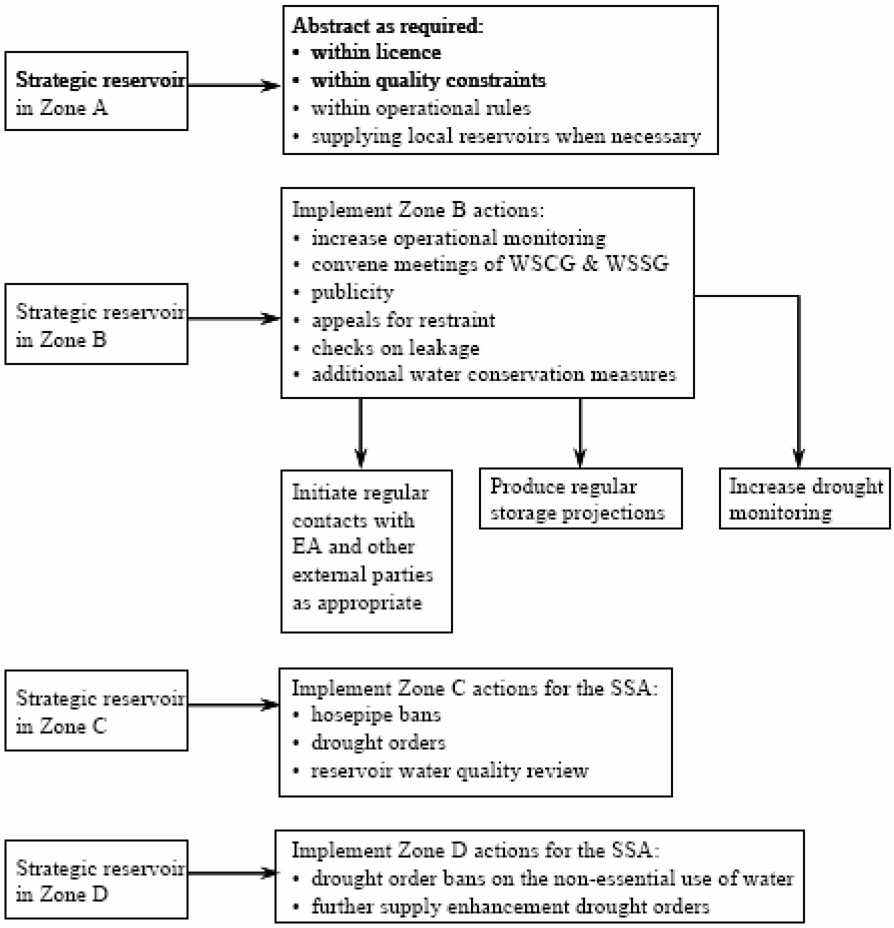


Figure 3.5 Actions for different zones for strategic reservoirs

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 a workshop setting. The following data are available for the Wimbleball SSA:

- Reconstructed river flows from 1865 from Jones et al., (2006a)
- Naturalised river flows for Exbridge, Wimbleball and Thorverton for 1955-2006 provided by SWW
- Reservoir, abstraction and demand characteristics suitable for detailed ‘behavioural modelling’ of the reservoir and/or water resources zone

In addition to this information other hydrological data such as spring flows and groundwater levels were 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 were consulted directly to gather the latest thoughts on likely demand reductions during drought conditions and other information, which supports the drought plan. This information was mainly used for preparing to test the drought management system in a workshop described in Chapter 5.

3.2.3 Water resource models

For Wimbleball SSA several different modelling systems have been used by SWW to simulate the impacts of drought conditions on water resources and the effects of introducing various demand and supply measures. Furthermore the Environment Agency has recently developed a water resource model for Wimbleball using LancMOD for climate change research purposes.

SWW currently uses the commercial model “Miser” for undertaking water resource modelling for Wimbleball. Miser is a modelling system which can simulate system behaviour, maximise conjunctive yield, safeguard supplies and minimise cost. A LancMOD model is also available for the Wimbleball SSA developed by the Environment Agency although this model has not yet been validated or compared against SWW’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 have not been made available 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 determined 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. Similarly to 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 Wimbleball reservoir system is generally more complex than the Grafham system due to the use of a pumped storage scheme for the winter period and the fact that most of the storage is used for flow releases for river abstraction in the summer. 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 SWW with reasonably good agreement. A daily model was also developed for 1975/76 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 the fact that 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.

Due to the fact that the model only covers 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 official 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 resource 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 also reflects the likelihood of increased baseline demand during droughts.

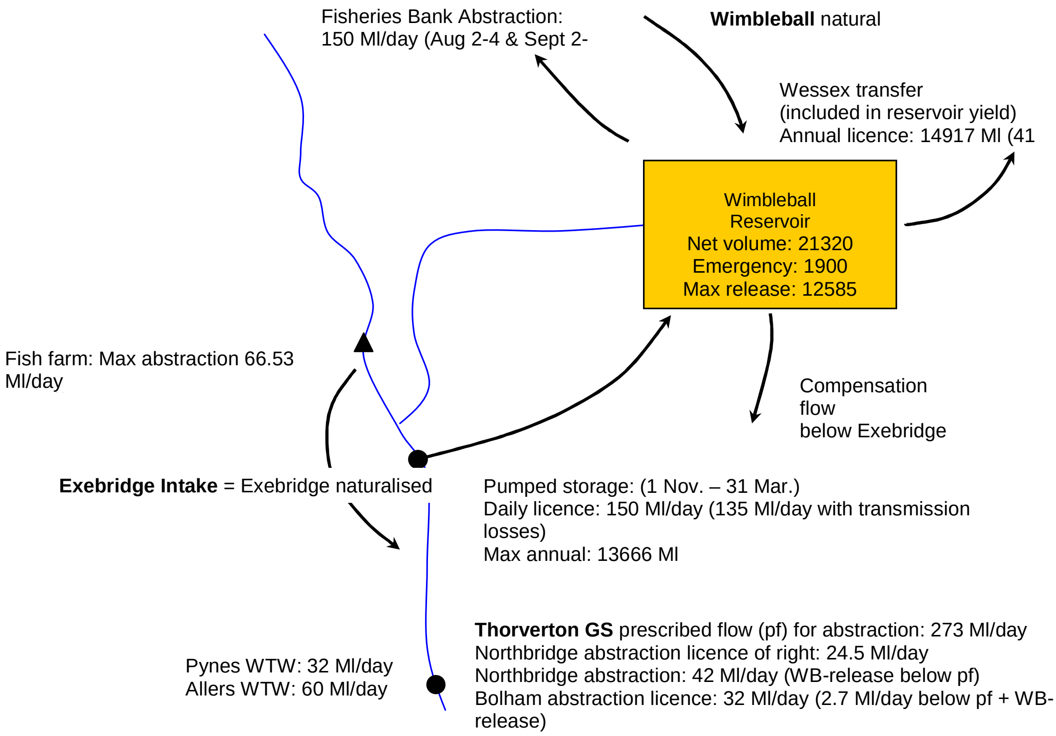


Figure 3.6 Schematic of the Wimbleball water resources system

3.3 Data and model limitations

A number of data and model limitations were identified during the development of the water resource models. These are discussed in the following:

- **Using a monthly time step.** The use of a monthly time step in the models was required in order 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. Due to the monthly time step these minor features are not adequately presented in the model.

- **Modelling approach used for re-constructed flows.** It is important to be aware of the uncertainties related to the modelling approach that were clearly highlighted in the previous 'Severe Droughts' work. Monthly rainfall data was collated from the MetOffice 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 it was considered whether the earlier drought could be reconstructed in any reliable way for the Exe. However the re-construction 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.** For the droughts from the early part of the 19th century the climate and hydrological data may not be very reliable. Available climate and hydrological data is discussed further in Appendix F. Furthermore limited supporting hydrological data such as groundwater levels and spring flows as well as anecdotal evidence of environmental impacts of rivers and aquifers are available for UK catchments for this period. Environmental impacts may however be assessed based on more recent droughts with similar characteristics.

- **Setting target demands.** Due to the simplicity of the models and consideration of only part of water resource zones normally used for water resource and drought planning by the water companies, it has been 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 explicitly considered 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 been 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 have been considered in the methodology used for testing the system described in Chapter 5 and in developing recommendations for improvements to the drought framework, presented and discussed in Chapter 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 (8 – 10 month) duration 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 on southern England, where replenishment of reservoirs and groundwater recharge in winter is critical for water resources. However, in these areas, the greatest impacts are likely to occur when two or more dry winters occur successively. The ‘severe’ droughts project (Cole & 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 & Marsh, 2006; Marsh *et al.* 2007b) noted that the droughts with the greatest impact on water resources were generally multi-year events. These authors observed that 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 (for example, in the 1890 – 1910 period), which therefore 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 has been 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 – 6). 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. Whilst in broad terms the concept of drought is readily recognized 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 resource management options and patterns of water usage can make for substantially different vulnerabilities within any given region.

There is an extensive range of existing drought indicators available (Hisdal *et al.* 2004, provides 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, and the geographical region where the analysis is being applied.

For this study, a range of existing, widely-used drought metrics was employed to facilitate the identification of long droughts. Appendix C provides details of the various methods which were 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 have very long runoff records, the majority of metrics are selected for their suitability for using river flow data, although most of the indicators can also be applied to other data types. Some metrics that are based primarily on meteorological data were also considered, and these are also discussed in Appendix C.

4.3 Characterisation and identification of long droughts

In this section, the drought metrics described in section 4.2 and appendix C are applied 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 the appendix.

The aim is to identify those droughts which can be considered 'long' droughts, and to explore mechanisms for characterising their severity and duration using available indicators.

4.3.1 Runoff deficiencies

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

A notable feature of the results, which agrees with results from the shorter periods used in previous work, is the prevalence of events from the 19^{th} century and early 20^{th} Century (particularly in the case of the Ely Ouse). For the Ely Ouse, over both the three- and five-year timescale, the four greatest deficiencies are from before 1910. Particularly notable are the two 36-month deficiencies within the 1802 – 1808 period, a sustained period of suppressed runoff; and, similarly, the two 36-month deficiencies within 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 this period also warrants attention as a period of persistent deficiency. The high rankings of the 1812 – 1817 period (not considered a major drought by Cole & Marsh due to lack of evidence of impacts) suggests this also warrants inclusion as a notable long drought for the Ely Ouse catchment. The major deficiencies of the twentieth century agree with those identified over 18-month durations by Cole & 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.

Table 4.1 Maximum 36- and 60-month runoff deficiencies for the Ely Ouse (synthetic Naturalised series from 1801 – 2002). Deficiencies before 1910 are in bold.

36-month deficiencies				60-month deficiencies			
Rank	Runoff (mm)	% of LTA	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				

Table 4.2 Maximum 36- and 60-month runoff deficiencies for the Exe (synthetic Naturalised series from 1865 – 2002). Deficiencies before 1910 are in bold.

36-month deficiencies				60-month deficiencies			
Rank	Runoff (mm)	% of LTA	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			

Whilst 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 & Marsh, 2006). In comparison with the Ely Ouse, there are fewer deficiencies from before 1910, with higher rankings thus attributed to the major twentieth century droughts, such as 1962 – 1965 and 1931 – 1934. This is partly due to the shorter record considered in the analysis.

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 & Conway, 1997; Marsh *et al.* 2007b) compared to the 1900s. Protracted periods of winters with depressed runoff are evident, including from 1800 – 1820, 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', 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.

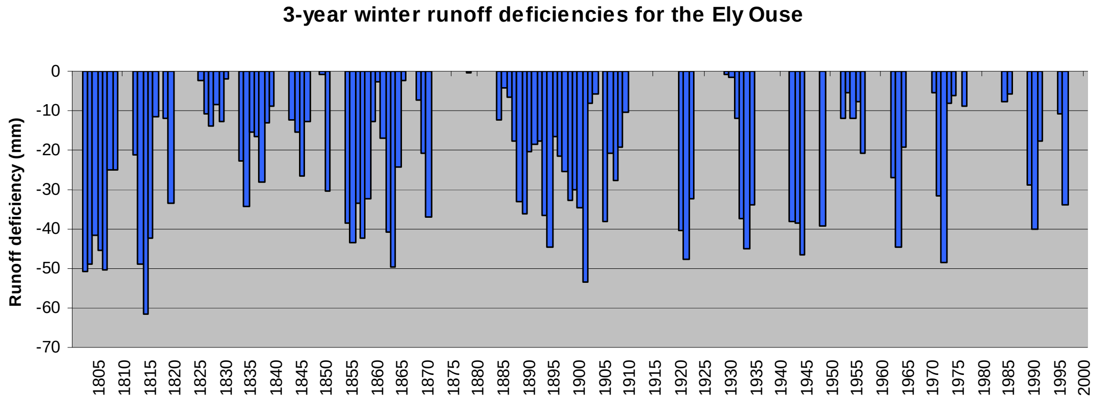


Figure 4.1 Runoff deficiencies for the November to April period, averaged over three successive winters

4.3.2 Drought Severity Index (DSI)

The DSI emphasises a key 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 are built 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-on-month variability in flow, 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 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[2].

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.

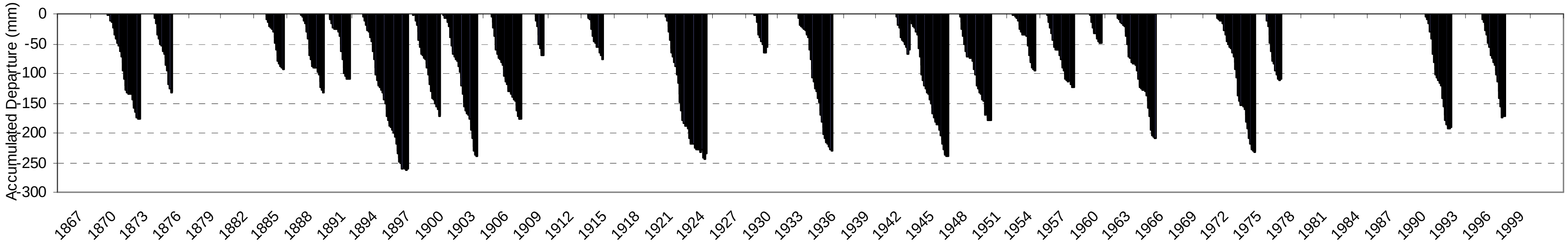
[2] The BFIHOST for the Ely Ouse is 0.74 (Marsh & Hannaford, 2008). BFIHOST is a measure of permeability estimated from soil properties, and in the case of this catchment is more representative than the BFI (0.46) derived from the flow record, which is heavily influenced by complex water transfers and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

The DSI extending back to 1803 for the Ely Ouse is shown in Figure 4.3. Figure 4.3 shows 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, as opposed to being identified as separate periods using the *n*-day approach. The relative magnitude of the various drought events (whilst 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 twentieth century, where several droughts of three years (or more) are separated by relatively short periods. The clustering of droughts in this period, whilst 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.

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, which is relatively close to the Ely Ouse catchment. The Cambridge rainfall series demonstrates that the 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, as 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 congruency 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 the DSI applied to the Therfield Rectory groundwater record. This borehole, in the Chalk of Hertfordshire, is one of the longest groundwater records on the National Hydrological Monitoring programme database. The site is in the headwaters in the far south of the Ely Ouse catchment. It should be noted that 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 of Bryant *et al.* 1994. Generally, the extended periods of groundwater deficiency correspond to the long droughts identified using runoff records. The impacts of long dry spells on groundwater levels is 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 is 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

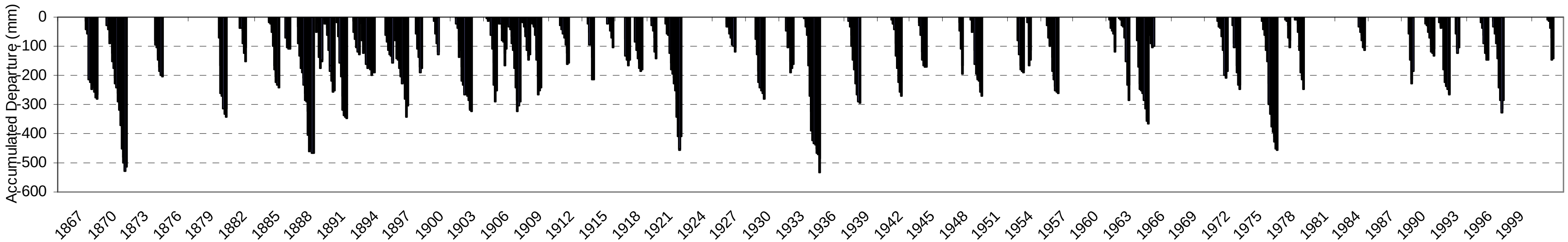


Figure 4.2 Drought Severity Index (after Bryant *et al.* 1994) based on accumulated monthly departures from the monthly mean, for the Ely Ouse and Exe reconstructed records (1865 – 2002).

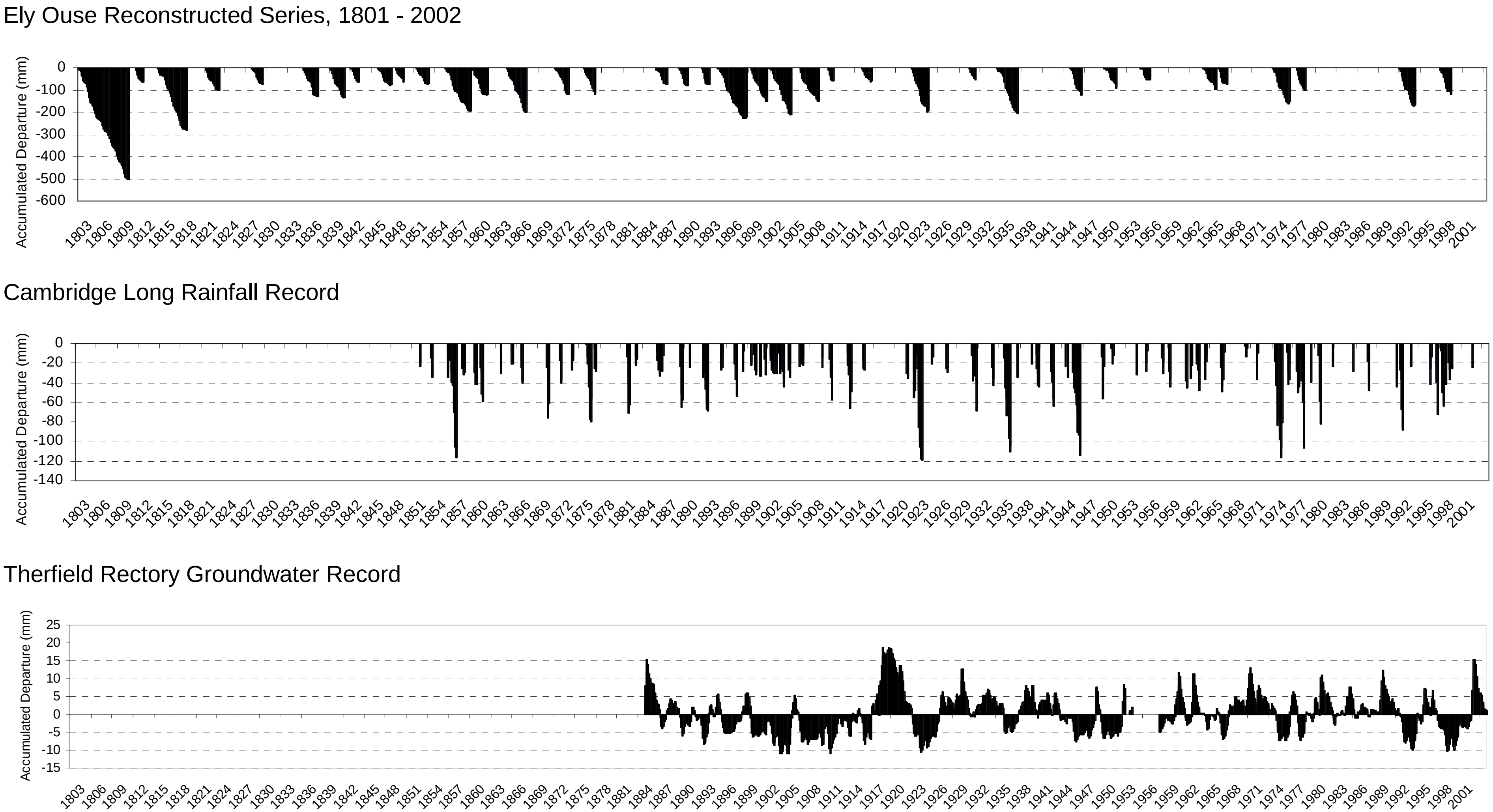


Figure 4.3 Comparison of Drought Severity Index for runoff, rainfall and groundwater records

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 threshold, for the Ely Ouse and Exe respectively. In general, similar events are identified as when the 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 was used). For the Ely Ouse, only the top two events extend over more than two years, but there are five droughts which had 18-months below the monthly-varying Q70 threshold, four of which 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 (m3/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	59.0
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 (m3/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

Table 4.5 shows the top 10 drought events (as ranked by duration, as the principal aim is to examine long droughts) identified by the 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 identical to 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 10 longest droughts according to the Sequent Peak Algorithm (SPA) analysis, for the Ely Ouse at Denver Sluice

Rank	Date	Duration (months)	Volume (m3/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. the SPI averaged over a 12-month period) is shown 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 twentieth century identified using the reconstructed records, e.g. pre-1910, 1940 – 1945, 1963 – 1966, the early 1990s. The plots neatly demonstrate 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 to historical droughts.

The regionalised version of the SPI (rSPI) and the Regional Drought Index for South East England are shown in Figure 4.5, an output from the drought catalogue produced by the spatial coherence project (Lloyd Hughes *et al*. 2009). 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% of the region was in a meteorological drought for several months; similarly, 60% or more catchments were under drought (below a daily-varying Q90) for long periods, e.g. late 1995 – early 1996, or during the spring of 1997 when more than 90% 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% of the region was under drought for over 9 months.

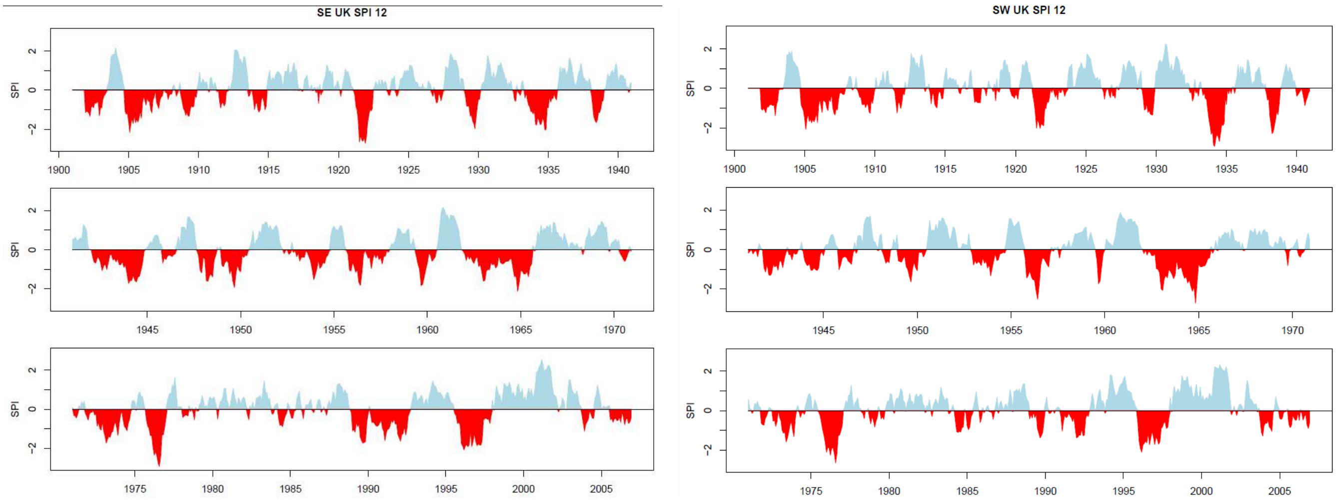


Figure 4.4 Time Series of SPI12 for two regions, south west England and south east England

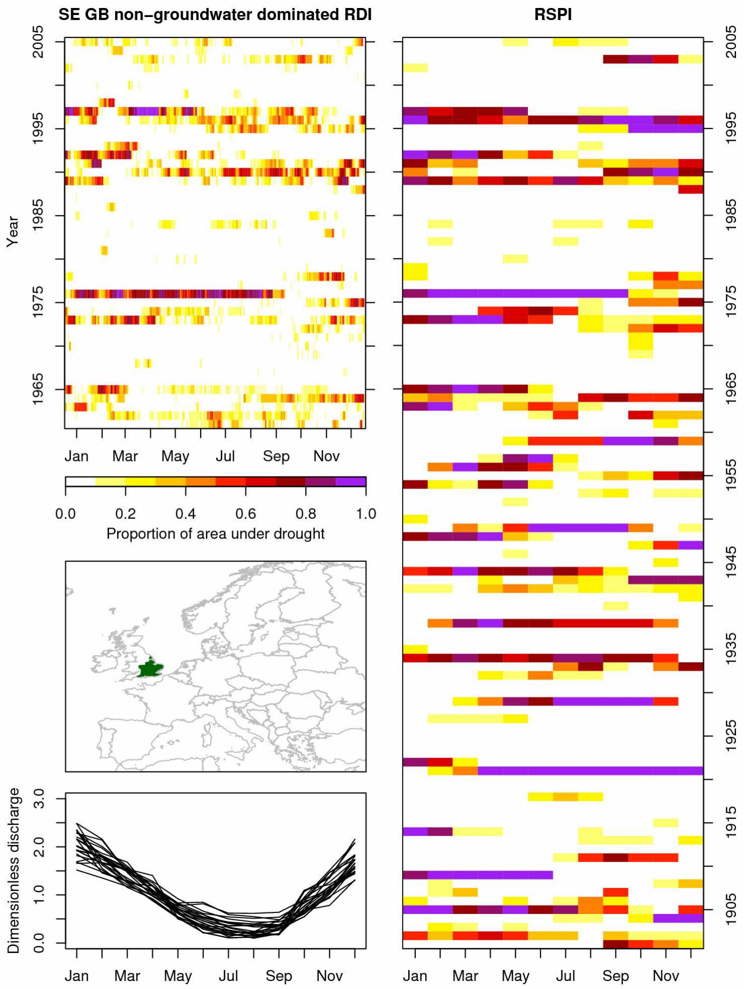


Figure 4.5 Example of a Drought Catalogue Page (Lloyd Hughes *et al.* 2009) for South East Great Britain

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 'major droughts' study considered the impact of historical droughts, but focused primarily on impacts on water resources (see Cole & 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 – for example, 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 and 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 100% of 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 NO3 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, the dissolved oxygen capacity of water, and 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 report that the river Exe at Thorveton was 6℃ warmer in June 1976, as compared to the same time in 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 in fungi, which in turn reduced the dissolved oxygen content (DOC) of river water at the height of the drought. This same expansion of water-borne micro-organisms was further aided by elevated water temperatures of 16-18℃ (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 1988-92 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 1988-92 was unprecedented in the twentieth century (Marsh *et al.* 1994).

Geological setting can play an important role in determining the extent of network shrinkage. Rivers in catchments with lower storage potential (impermeable geology) are more vulnerable to reduction in the extent of the drainage network than streams supplied by more sustainable spring outflow sources (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% of its original 1094 km length (Doornkamp *et al.* 1980). However, 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 reports exist of down-valley recession during historical long droughts (e.g. in 1921, when the Kennet retreated 16 miles downstream; BHS, 2009). Cole & Marsh (2006) synthesise a range of anecdotal evidence of the long drought periods from 1890 – 1910, and dry wells and springs feature prominently as recorded impacts. The Wendover springs, a rare example of a springflow record with data from the turn of the twentieth century, was reported to have dried up repeatedly during this period (Bayliss *et al.* 2004).

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% of right bank tributaries had run dry, but only 44% 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 1988-92; 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) mechanisms (Clayton *et al.* 2008).

4.4.3 Hydro-Ecological Impacts

Prolonged or severe drought conditions can trigger changes in the micro-biological 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 lead to drying up of rivers and ponds - fish rescues were needed in isolated and declining stretches of river (Marsh *et al.,* 2007a).

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 whilst drift-feeding.

Only a limited amount of work has been done 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 had an impact on habitat availability, compared to the more typical conditions for 2004, on the River Kennet. In 1976, however (when flows were the lowest in a 45 year record) the habitat availability was much reduced. In the latter case, a very dry winter combined with an extremely dry summer and associated heatwave, which served to exacerbate the impacts of the drought.

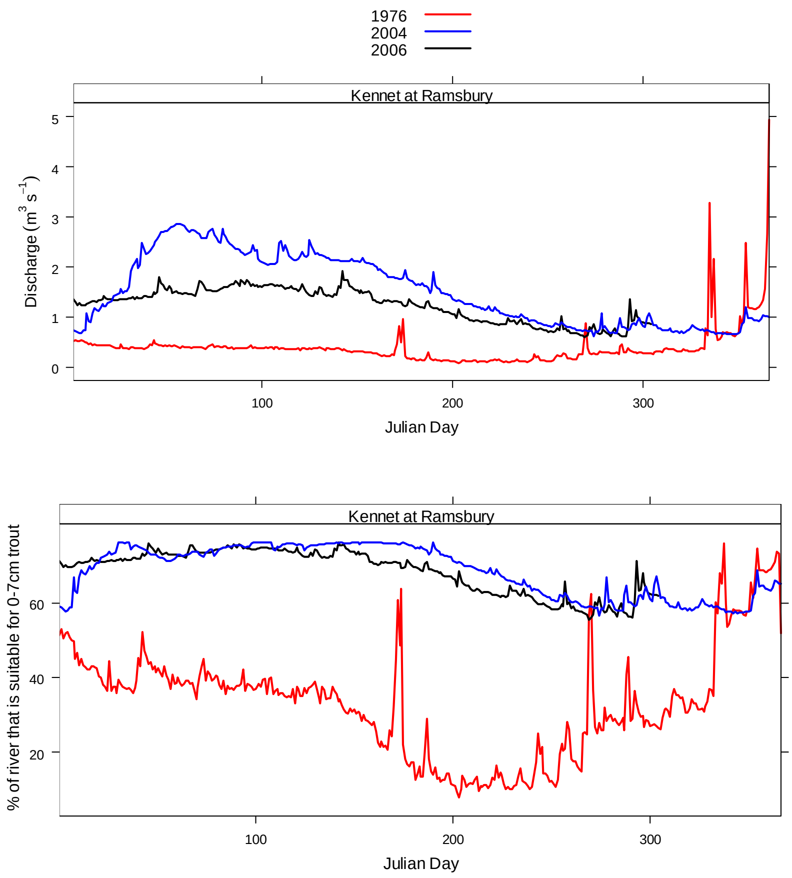


Figure 4.6 A comparison of habitat availability in 2004 and 2006, and 1976, on the River Kennet (from Marsh *et al.* 2007a)

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 to the vast range of material assembled on agricultural and other socio-economic impacts (e.g. Doornkamp *et al.*1980. Reports carried out 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 & Marsh, 2006), and Marsh *et al.* 2007a provide some background information on ecological impacts of the 2004 – 6 drought. In particular, there are very few sources, which 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 briefly discusses 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. 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 to historical periods. Deficiencies expressed relative to a long-term average are widely used in drought monitoring; for example in the Hydrological Summaries produced by the National Hydrological Monitoring Programme (CEH, 2009) and the EA's Water Situation Reports. Figure 4.7 shows runoff deficiencies during the 2004 – 2006 drought, based on an accumulation from November 2004 – August 2006. For each of these catchments, the runoff over this period is compared to 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, clearly highlighting the exceptionally low runoff seen in Southern England.

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 3-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. Importantly, however, the termination rule should be hydrologically meaningful; 3 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 for comparing 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 resource provision in different regions and water supply systems. Future research should be directed at developing a more sophisticated version of the DSI, which employs termination criteria relevant to particular systems – for example, a version which gives higher weighting to winter rainfall deficits in groundwater areas which are dependent on winter recharge.

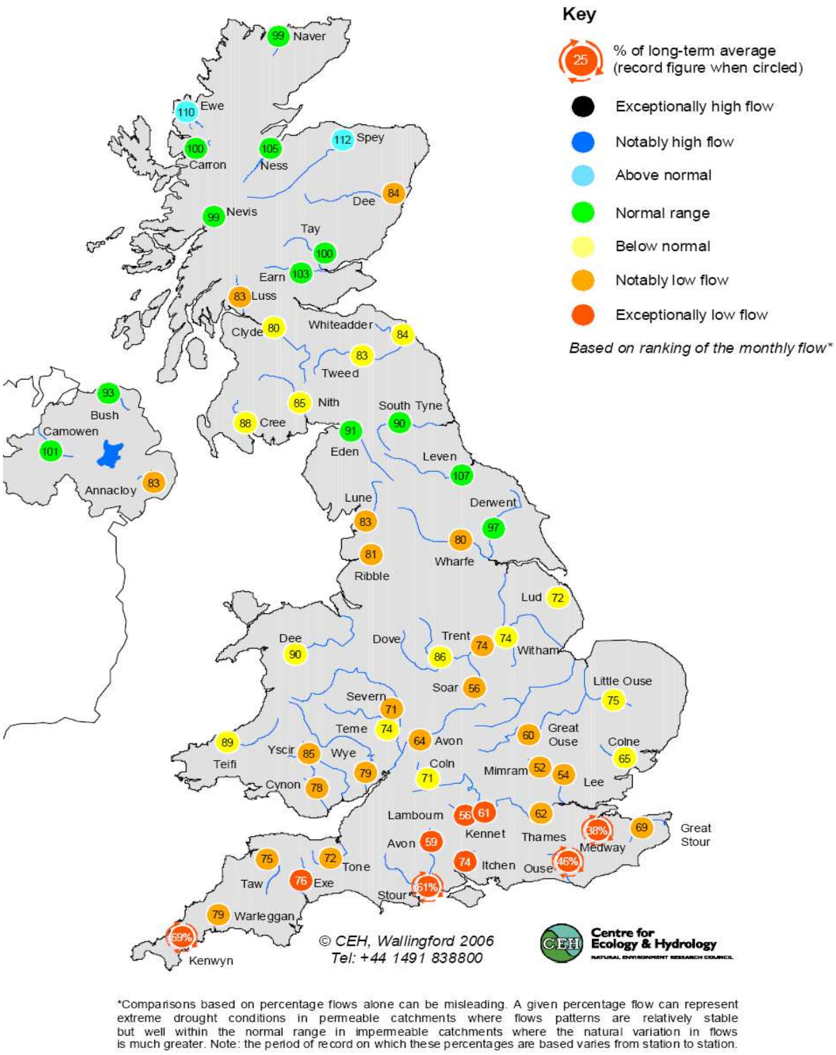


Figure 4.7 November 2004 – August 2006 runoff accumulations as a % of the long term average (from http://www.ceh.ac.uk/data/nrfa/water_watch.html)

The threshold method and SPA have high utility 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.* 2009). 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, but the parameters used to characterise the events (duration and maximum deficit volume) are still dependent on the configuration of the methodologies. Whilst 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 (see Figure 4.8; cf. Figure 4.4).

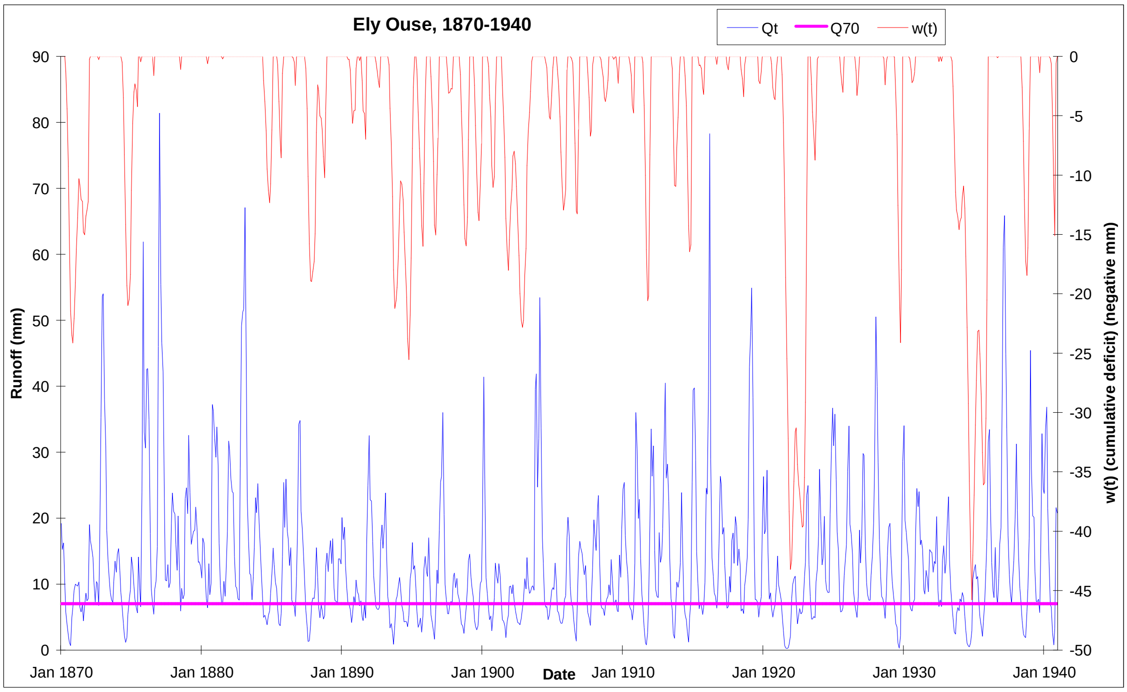


Figure 4.8 Illustration of droughts identified using the Sequent Peak Algorithm for the 1870 – 1940 period

One weakness of all these hydrological drought indicators is that they only provide a mechanistic view of the severity of a drought event, and provide little indication of the nature of the drought in terms of impacts. Furthermore, within this project the metrics have been chosen 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 only characterised 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 the DSI and SPA. However, this deficiency did not result in major societal impacts and was not considered a major drought (Cole & Marsh, 2006). In contrast, 1975/76 only ranks 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.

The SPI and PDSI are discussed briefly (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 & Saunders, 2002), and is frequently used 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 Centre, and a part of 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 has established pronounced changes in the seasonal distribution of rainfall
- The results agree with the major historical droughts identified by Cole & 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 – 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 19^{th} 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 to 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 has been tested for severe historic droughts in a workshop setting for the two catchment studies with attendance from the Environment Agency, the water companies and Defra. The methodology is illustrated in Figure 5.1 and included several steps in terms of preparing data and models for the workshops, interpreting the outputs from the workshops and identifying gaps and/or weaknesses in the current drought management system.

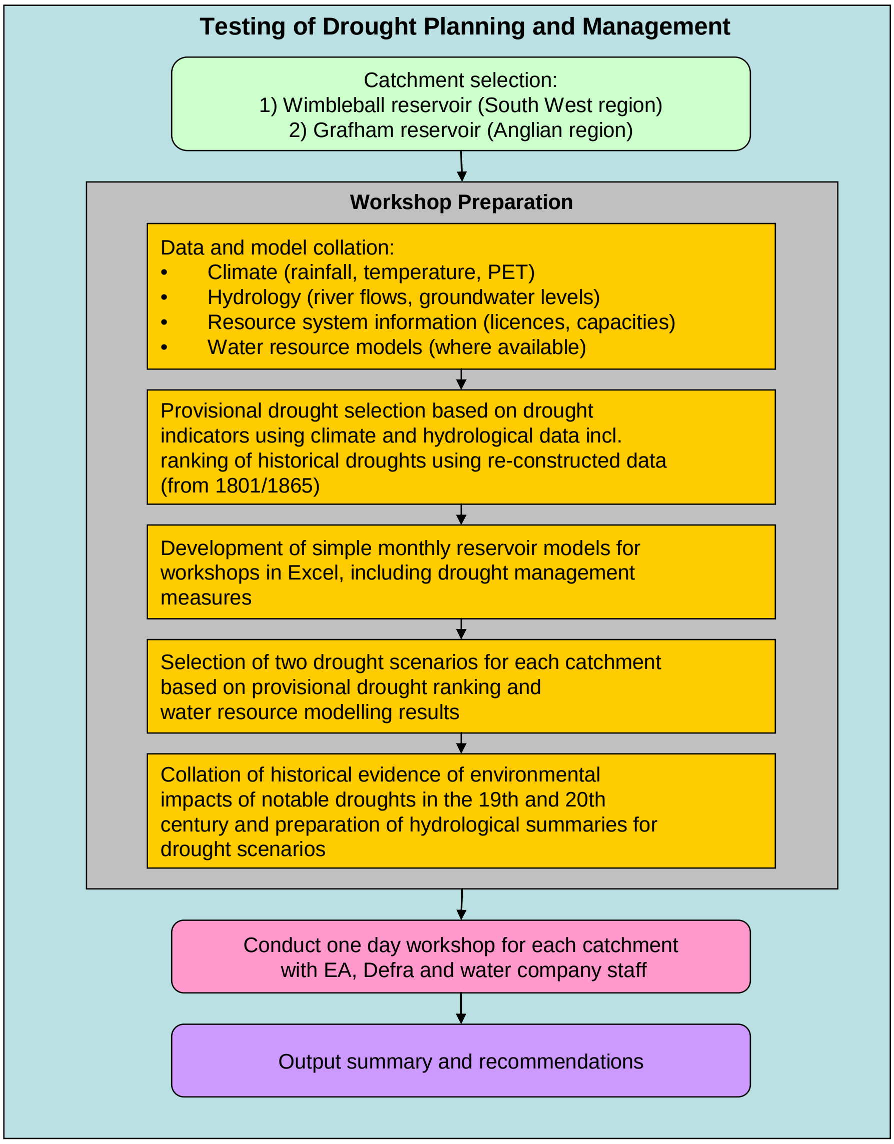


Figure 5.1 Illustration of the methodology used for testing the UK drought management system for two selected catchments: Wimbleball and Grafham reservoirs

During the workshops water resource models were used for playing through two drought scenarios with input from the water companies, the 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 taking the impacts on the environment into consideration.

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

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 to think 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 the hydrological and water resource data as it emerges and a focus on how this affects the decision making of the water company, the Environment Agency and Defra would be more appropriate. However, even this much simpler approach required detailed preparation so that the data presented ‘worked’, the model results were presented in such a way that the participants would find it easy to understand and make decisions and the scenarios were believed to be plausible by the people involved.

Two simple water resource 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 also provided including rainfall, groundwater levels and river flows which was presented using the standard Environment Agency head office classification 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 6 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 3-7 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. The Environment Agency and Defra then, on the whole, waited to hear from the water company 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 resource 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); and
- Overview of the day.

The workshop design is described in further detail in Appendix G, which also includes general guidelines on running these types of drought management exercises. An example of actions taken during the workshop with SWW for Wimbleball reservoir for one drought year is also 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.

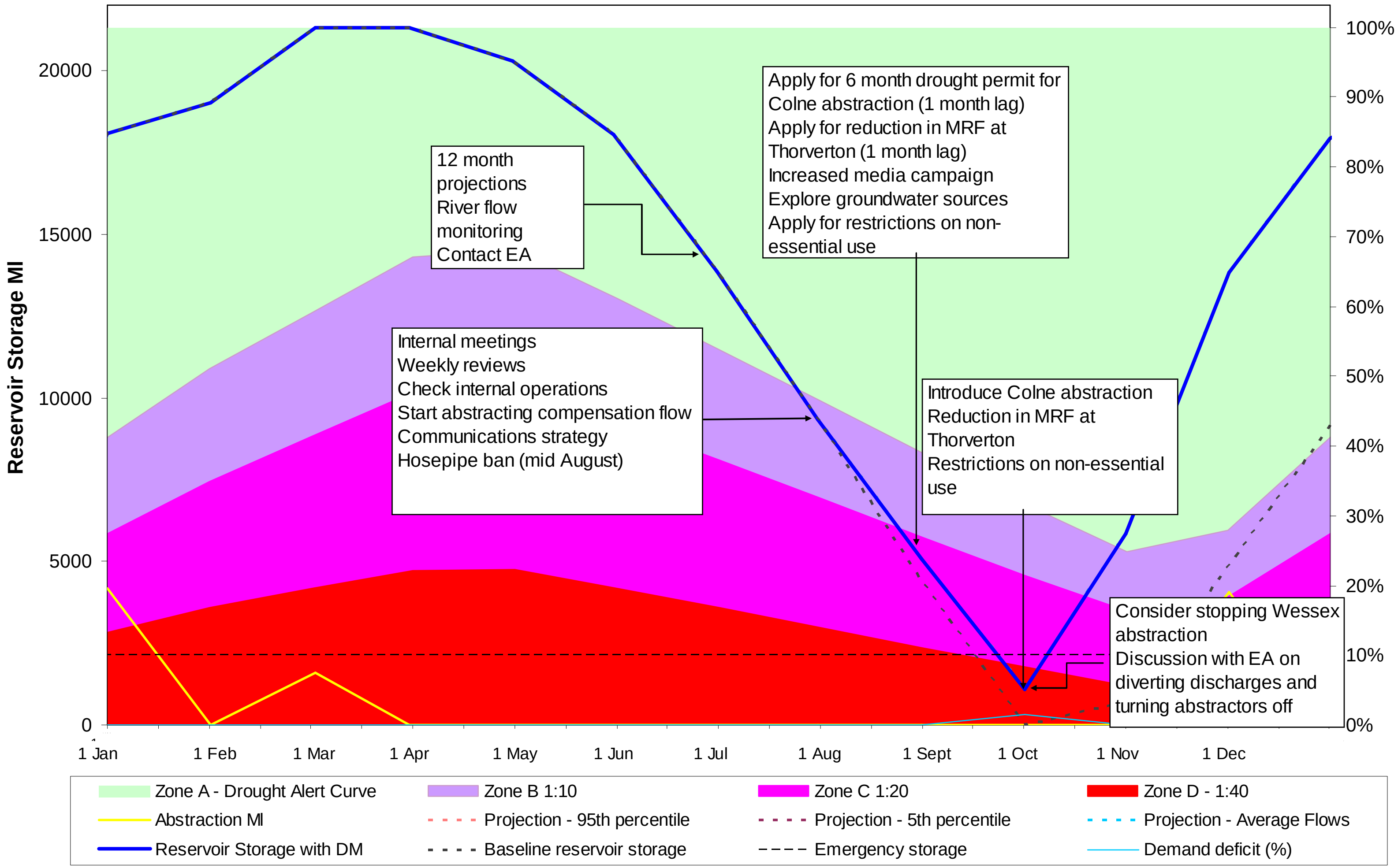


Figure 5.2 Example of drought actions taken during the workshop for Wimbleball Reservoir

5.3 Selection of drought scenarios

Two droughts with different characteristics were selected for each of the two case-studies in order to allow exploration of a wide range of possible actions and responses as these will depend on the on-set, 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 of the normal period that water companies use for drought planning purposes (normally 1920-2006). The selection of the historical droughts was kept from the participants as to prevent prior knowledge from affecting the decision making process.

5.3.1 Wimbleball

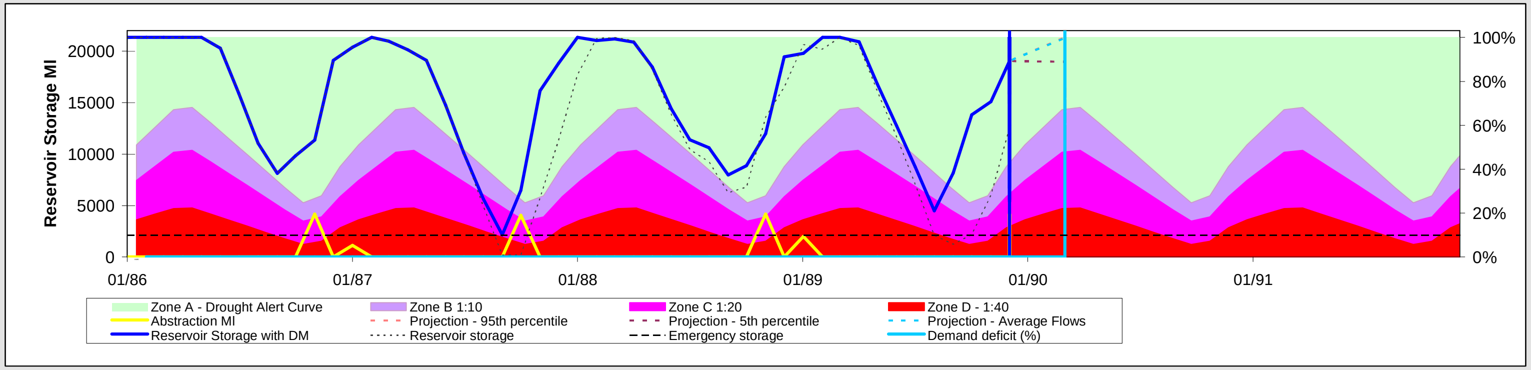
For the Wimbleball system the pumped storage scheme designed to refill the reservoir every winter means that droughts can essentially be treated as single year events. Running the simple water resource model for the period from 1865-2006 indicates that the reservoir is always close to 100% full on April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

In reality because demands are lower 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%. 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 -07, 1895 – 1898 and 1869-1870. In terms of reservoir drawdown the simple monthly model indicates that from a water resources perspective the droughts of 1869-70, 1887-1888 and 1895 – 1898 were the most severe. The droughts of the early 20th century were not significant in terms of reservoir drawdown, most likely due to more variable rainfall and resilience of the system to winter droughts. For the workshop the following two periods were selected: (1868-71) and (1886-87+1895-96).

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																						
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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 1990-91. 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 1990/91, 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 has been set higher than normal demand (150-155 Ml/day). This produces 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 reservoir 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 1896/7 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 has been changed somewhat following thorough 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 are different to those presented in the previous 'Severe Droughts' project. The most severe droughts in water resources terms occur during the period in the early 1800s and 1815-16. Although the 1800-10 falls within the "Little Ice Age" when temperatures were a degree lower the drought is still assessed 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 1807-08 and 1815-17 and the second scenario covers the 1801-04 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 1934-35 and 1976 droughts. The same applies to the second scenario which illustrates a less prolonged but very severe water resources drought. Due to smoothing of the results using monthly data, the likelihood of increased demand during droughts and to stress the system the demand used was set to 262 Ml/d, which is slightly higher than normal operations at Grafham but equal to the Deployable Output with demand restrictions presented in the company's drought plan (Scenario 3, AWS, 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 resource 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 of the respective drought plans.

There was a reluctance to place hose pipe bans on customers and 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 stand pipes and rota cuts was seen as unacceptable and sign of failure of the water resources system. Tables 5.1 and 5.2 below 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 to 1871 drought	**Scenario 2 High demand with 1886-87 plus 1895-96 drought**
Drought characteristics	o Three dry years with successively drier summers/autumns o Rapid 'speed of onset'/drawdown o Years 1and 2 within company experience but **Year 3 was 'unprecedented'**	o Four dry years with a severe drought in years 2 and 4 o Rapid onset with short winter periods with full reservoir stocks o **Outside company experience**, particularly years 2 and 4 that required wide ranging drought management measures
Supply	o Significant additional supplies needed for 2-3 months in third autumn o **Used emergency measures outside of drought plan**	o Significant additional supplies needed in Year 2 o Further supplies needed for 2 months in Year 4 o **Used emergency measures outside of drought plan**
Demand	o Hosepipe ban used o 15 percent reduction in demand	o Hosepipe ban and restrictions on Non Essential Use o Tried to reduce Wessex Water's demand – possible Drought Order o Potential for temporary licences to speed up response o 19 percent reduction in demand
Operational	o Use of monitoring, projections, liaison communications, leakage reduction o **Questioning drought trigger approach – need methods for including these events in drought planning**	o Use of monitoring, projections, liaison communications, leakage reduction, re-zoning o Much better working withEnvironment Agency and other regulators o **The importance of hydrological reporting and use of drought projections highlighted**
Other issues	o **Supplies seriously threatened in third year of drought** o **No public water supply failure** o Main environmental concern related to fisheries and operation of 'fish bank' o **Drought management framework worked effectively in Years 1 and 2 but tested in Year 3 – the water company had to use emergency measures outside of drought plan** o National political interest	o **Supplies seriously threatened over several years** o **No public water supply failure** o **Some drought powers e.g. HPB could have been used earlier in Year 4** o Main environmental concern related to fisheries and environmental impacts year on year with two severe drought episodes o **Drought management framework tested to breaking point – measures used outside of plan to maintain supplies** o Defra concerned/asked whether water resources management system is flawed. o 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 - 1815/17	**Scenario 2 High demand with 1801 to 1804 drought**
Drought characteristics	o Long drought lasting almost 5 years and punctuated by very dry November to April periods that are important for reservoir refill o Individual hydrological drought episodes were no more severe than 1921/22 or 1933/34 or 1976 drought periods o However the hydrological drought with high demands (262 Ml/d) created difficult water resources management conditions	o Long drought with high demand (262 Ml/d) – most severe water resources drought for 200 years – causing rapid unprecedented drawdown of Grafham o **Drought outside the range of normal company experience – how to include these in Drought Planning? Re-calculation of DO for WRP could be necessary.**
Supply	o Operational improvements o Required balancing across zone – use of WRP headroom o **90 Ml/d including MRF reduction** (70 Ml/d plus 20 Ml/d from Rutland)	o Operational improvements o Required balancing across zone – use of WRP headroom o Emergency plant – effluent re-use o Operation Rodeo flow reversal o **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 rodeo 10 Ml/d)
Demand	o Hosepipe ban o Voluntary reductions o **13 percent reduction**	o Hosepipe ban o Voluntary reductions o Non-essential use reductions o **19 percent overall demand reduction**
Operational	o Rutland used to balance supplies o Leakage control o Benefit of using available headroom / outage allowance	o Wing WTWs used to balance supplies with available headroom o Leakage control o Benefit of using available headroom / outage allowance
Other issues	o Environmental impacts on Ouse Washes – Risk of infraction proceedings o Refusal of MRF reduction at Offord until NEU granted o Spray irrigation and agricultural restrictions were introduced by the EA in collaboration with the farmers to reduce environmental impacts	o Speed of onset of drought challenging for water company and would have been problematic had the reservoir failed o Spray irrigation and agricultural restrictions were introduced by the EA 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 was seen as a key priority for water companies and the Environment Agency during a drought. It was perceived that it would take up a significant resource in terms of people's time (media training, interviews, preparing messages and materials etc.) and the organisations 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 hose pipe 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 companies supply network.

The communication of *in extremis* measures was also a key concern to 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 hose pipe 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 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, the EA and Defra

Although the three organisations had different motives and core purposes there was a general acceptance that, in an extreme situation, 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.[3] In the workshop for Grafham the Environment Agency 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 this 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. hose pipe bans or restrictions on non-essential use.

There was a sense (expressed more strongly in the workshop for Wimbleball) that in a drought there would be a 'we're all in this together' attitude prevailing and that the Environment Agency and water companies would band together to work out the best strategies. Personality, experience, institutional memory, rapidity of staff turnover may have an important part to play in building these effective links (and more intangible

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

elements such as ‘respect’ and ‘trust’) between the different players and 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 to educate others in the three organisations, who do not work directly with drought, was mentioned. This was important so they would understand the knock-on effects of drought for their work and also they would be primed to understand how resources in the organisations might have to shift, especially if the drought was prolonged.

There was some frustration expressed 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 but not always more severe than 1921/22, 1933/34 and the 1976 droughts used by the companies for planning. 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 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. AW were confident that headroom could be used for providing additional water from other parts of the catchment (for example from Wing WTW (Rutland) to Grafham). If however 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 (a) early recognition of a potential threat to water supply and (b) the time taken to implement measures due to operational and legal constraints (particularly for the SW example).

The close linkages between water resources planning and drought planning were evident through discussions. There was an arguably over-simplified view that WRMP and Drought Permits must be entirely consistent in terms of design conditions on demand and Deployable Output, which 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

Themes that came up in both workshops included (i) 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 and (ii) what water companies and the Environment Agency need to cover in their respective drought plans. There was a request for more explicit guidelines on how far to go in to extreme droughts in company drought plans. It is clear that as you become more risk averse (by increasing DO and headroom as part of the WRMP process or avoiding drought restrictions) your systems are likely to fail less frequently but when they do, the failure can have dramatic consequences.

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. In both workshops participants expressed concern about how the public and special interest groups would react to these if they were detailed in the drought plan as they are controversial and the likelihood of needing them very low ('the public would be apoplectic'). 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 long drought situation.

The question of how to present innovative ideas/emergency measures for the 'worst case' low probability events was raised in both workshops. At the moment there is no clear request that such measures should be included in the drought plan but there could be a section in the plans 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 that these measure would ever be used.

It was clear 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 thus a need for flexibility in the planning system to allow for this but this is difficult to communicate in the drought plan. There clearly needs to be a balance between transparencies of potential interventions, for example clear information about what the water company is planning and accountability, without increased burdens of paperwork and over elaborate processes that divert attention and further stretch the limited staff resources and time available to respond during severe droughts.

Headroom, which is used in water resources planning to deal with uncertainties and risk, was perceived in the AW workshop as being 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.

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, Nevertherless a combined drought and outage scenario may provide a worthwhile test for drought plans, keeping in mind the combined probability of this event will be low.

In the SWW workshop it was suggested that in the depth 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-authorising access to avoid having to use Drought Orders [drought orders can authorise access, drought permits can't], and getting temporary licences in place of Drought Permits and Drought Orders. It was suggested that attention could be put towards 'smoothing' the progress of applications for Drought Orders and drought plans in anticipation of them being needed. Those who might object could be brought in before the application was made so any objections could be dealt with in advance. When it was needed the application would thus go through unimpeded. Concerns have been raised by AW that this would not work in practice and that a better solution would be to vary abstraction licences based on triggers, e.g. so that MRF 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 that were 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 in the SW 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 (prob. X consequences) are clearly understood and a range of flexible drought planning and/or water resources planning measures 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.

Finally improvements to the quality of data provided by the Environment Agency were discussed in one of the workshops. Hydrological data using the Environment Agency categories (i.e. normal, below normal etc.) were found to be very useful (the workshop scenario used data provided by CEH incorporated this method). There may be a need for 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 and while there may a longer term potential in using Met Office weather predictions a more immediate need to improve flow forecasting methods using simpler rainfall and flow projection techniques was identified.

6. Recommendations

Based on the workshop findings and further discussions with the Steering Group, the project team has identified a number of gaps in the current understanding of long droughts that may 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 project 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 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, which (i) cover all of the drought management processes and measures applied during periods of drought and (ii) 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

A number of recommendations for improving current drought planning guidance have been identified:

- **Drought planning guidance should emphasize 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, although these measures were included in the 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).
- **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 measures and actions 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 the 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, for example 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).

- **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 made aware 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 EIA and monitoring plan as well as liaison with the Environment Agency is estimated to speed up the application process from 4- 6 weeks to 1-2 weeks. A need for further joint EA/Defra guidance to clarify the difference between drought permits and droughts orders was also identified in 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 for example 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). 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, for example 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 resource 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 amongst both the water companies and within the Environment Agency. The Environment Agency have indicated that some minor changes are required to the current licensing system to enable water companies to apply for temporary licences but in some circumstances this could be a useful alternative to applying for drought orders which tend to be more time consuming and costly.

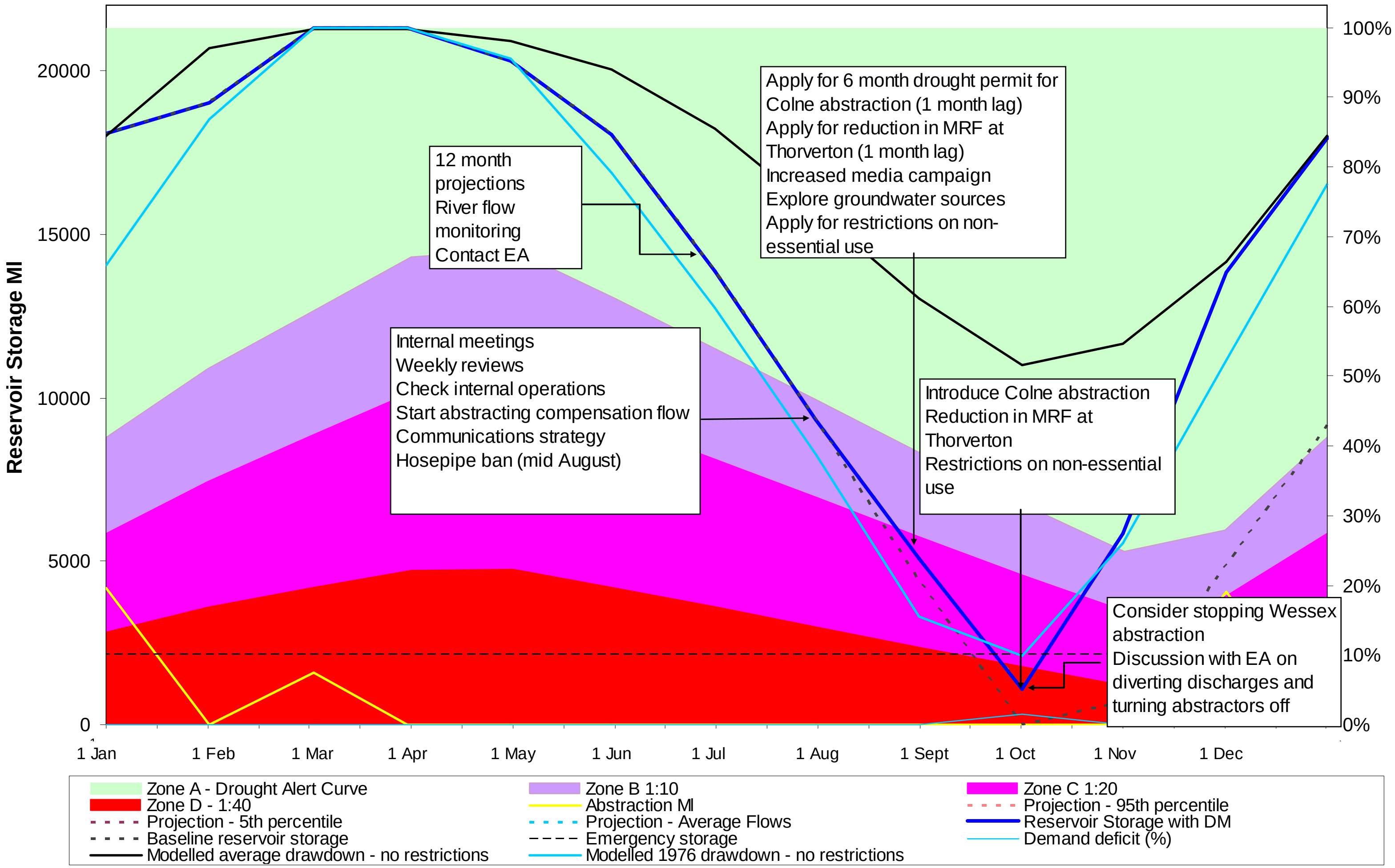

Figure 6.1 Illustration of Wimbleball reservoir behaviour under average and drought conditions (1870 and 1976)

6.2 Further research

A number of research recommendations have been 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 the water company concerns are valid or public perception could be improved by more transparency. A better understanding of the public's and water customer's attitudes 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 Overall Performance Assessment (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 resource systems. Multi-variate triggers could be considered looking at not just rate of decline in reservoir levels but also demands and perhaps river flows 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 resource 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 Resource 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 Resource Plans (WRPs). 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 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 in 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.

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List of abbreviations

AMP	Asset Management Plan (a review of water prices associated with an agreed infrastructure programme)
AWS	Anglian Water Services
CAMS	Catchment Abstraction Management Strategy
CEH	Centre for Ecology & Hydrology
CRU	Climatic Research Unit, School of Environmental Sciences, University of East Anglia
Defra	Department for Environment, Food and Rural Affairs
DO	Deployable Output
DWI	Drinking Water Inspectorate
EA	Environment Agency
EU	European Union
GET	Generalised Environmental Trigger
LoS	Levels of Service
NR	No Restrictions
Ofwat	Office of water services
RBMP	River Basin Management Plans
SPI	Standardised Precipitation Index
SWW	South West Water
UK	United Kingdom
WFD	Water Framework Directive
WHD	Worst Historic Drought
WRP	Water Resource Plans

Appendices

Appendix A: Literature summaries

Author/Title	Anglian Water, 2008. Drought Plan
Scope	This document details Anglian Water Services' (AWS) latest drought plan in accordance with the Water Act 2003. The AWS Drought Plan follows on from their last non-statutory plan submitted in 2003 to the EA. It is consistent with the company's Water Resources Plan (WRP) which assessed the supply-demand balance.
Summary	**Drought management to date:** Water use restrictions were last imposed by AWS 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, for example 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 AWS has carried out since its last drought plan includes the Water Resources Plan 2004, their Draft Water Resources Management Plan and a National Environment Plan (NEP) to address environmental impacts of abstractions, looking specifically at the Ouse and Nene Washes. They also have the Water Resources Environment Programme (WREP). **Water resources planning:** Their WRP was submitted in 2004. This looked at Deployable Outputs (DO) as well as the supply-demand balance. The availability of headroom, which covers uncertainty in water resource calculations, is assessed in the Security of Supply Index (SOSI) every year. AWS has considered the potential impacts of climate change through the use of the UKCIP02 scenarios and indicate that they could be more severe than previously considered. Drought management supply and demand options are based on Water Resource Zones (WRZ), however a local authority basis will be use to implement demand management options. **Drought scenarios:** AWS 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 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. Their communications strategy is

	also implemented according to this. AWS has provisionally prepared three cases for Drought Orders in its plan. **Managing supply and demand:** Combining resource development with demand management strategies. Levels of service during drought conditions are used to measure this supply-demand balance against forecast demand. AWS' 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. AWS has applied for Drought Orders to refill Grafham and Pitsford during the winters in 1976 and 1997. However the first application was not needed and the second was withdrawn. AWS identified that new resources may need to be developed towards the middle and end of the 25 year planning period (as in the WRP) 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 methods which have also been implemented include the installation of water meters and leakage control. Coastal areas may experience a peak demand according to the season and the weather, as a result of tourism. **Groundwater:** Around half of AWS' customers are supplied 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 which is very important for water resource 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 AWS 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 and AWS has considered mitigation strategies including environmental support pumping.
Key Points	
Data Issues	
Comments	

Author/Title	Defra (2005) Drought orders and drought permits. Information from the Department for Environment, Food and Rural Affairs, Welsh Assembly Government and the EA
Scope	This document provides information on drought permits and drought orders and details what the process is 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. The available types are: ▪ Drought permits ▪ Ordinary drought orders ▪ Emergency drought orders Drought permits are granted by the EA, while ordinary drought orders and emergency drought orders are authorised in England by the Secretary of State or 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 in implementing demand-side management measures in accordance with the associated impacts on the environment (EA, 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 and drought permits/orders: The Environment Agency will take other water users into account when granting drought permits or supporting drought orders. It does however 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	Environment Agency (2005) Water company Drought Plan Guideline 2005 Version 2.0
Scope	Guidelines on statutory 2006/7 drought plans to be submitted by water companies in terms of content and structure. The guidelines have been revised from the EA's drought plan guidelines 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 been submitting drought plans to the Environment Agency, however now the process is statutory and they need to be submitted to the Secretary of State. 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 key issues that will have to 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 with a variety of parties including the Secretary of State/NAW, the EA, Ofwat and licensed water suppliers, before the plan is prepared. 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. This corresponds to the severity of the drought, for example 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 its resilience to a number of possible drought situations and therefore improve management planning. It must give reasons for choosing these scenarios. ▪ The plan needs to be consistent with the company's Water Resources Plan (WRP) in terms of deployable outputs calculated and levels of service used. ▪ How the drought will be monitored ▪ 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 Habitats

	Regulations Act. Environmental factors which could be affected by any drought measures as detailed 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 EA'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. ▪ How the company will provide information to its customers through its communication strategy. ▪ Actions to be taken following the drought must be highlighted and if there are any reviews needed of the plan then it should be updated. Potential sites for drought orders and drought permits should also be considered otherwise it is unlikely they will be granted or supported by the EA.
Key Points	The drought plan ensures the security of supply of water throughout a drought. Every water company should follow these guidelines in preparing their drought plan.
Data Issues	
Comments	

Author/Title	Environment Agency (2006). *Drought prospects 2006. February 2006*
Scope	The purpose of the report was to provide an overview of the water resources situation in England and Wales in February 2006 and provide recommendations for actions by water companies and other abstractors
Summary	The state of water resources was 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 but the situation was quite severe in all of south east of 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% of average) a number of recommendations for the water companies were put forward. These include: • 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 their drought plans and make sure that steps to save water are taken in good time. • Prepare to make drought permit and drought order applications in line with their 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 their 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 our internet site. • Update our 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 we can on the impact on agriculture, including possible restrictions on spray irrigation. • Take steps to protect the environment from drought, including: 1. Where we have them, using our river support schemes to maintain flows and protect wildlife; 2. Restricting spray irrigation where this will provide significant benefit to the environment; 3. 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 we believe 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. Also it is stressed that the water companies make their own decisions about measures but if advice from the Environment Agency is ignored the water companies must defend their approach to customers/regulators.
Key Points	Environment Agency recommendations should be followed by the water companies.
Data Issues	
Comments	It is *unclear* what the consequences may be if the Environment Agency advice is not taken (apart from application from drought orders by the EA.)

Author/Title	Environment Agency (2006a). Drought prospects 2006 – spring update. May 2006.
Scope	The purpose of the report was to refine the EA's view of prospects for the water resources situation in England and Wales in the summer of 2006, evaluate actions by water companies and 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 the 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%. Essex and Sussex were also assessed to be at risk although reservoirs were close to full because a hose pipe 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 EA) included hose pipe 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 have worked closely with the Environment Agency in publicity campaigns to raise awareness of the drought and encourage the saving of water. The hosepipe ban has resulted in negative reactions from gardeners indicating mismanagement of water resources by the water companies. Water saved by the ban has been much smaller compared to 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) have been extended. A table has been included in the report outlining actions taken by each company based on recommendations from February. The Environment Agency recommended further actions: • Essex and Suffolk Water should apply for a hose pipe ban in May • Portsmouth Water should monitor the situation closely • Other water companies (incl. Thames Water) should prepare to apply for non-essential use bans • Further work on leakage control in addition to increased levels of investment. The Environment Agency recommends investment above the economic level of leakage • Further drought permit applications were expected although wetter weather reduced the immediate need More general recommendations were also put forward, very similar to the original from February. The Environment Agency outlined their actions which were also largely the same. The report encourages the water companies to act quickly to make

	the best use of available water. Any delay could exacerbate the situation. Concerns of a third dry winter is mentioned. Dedicated drought teams were set up to manage the impact of drought and 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	Environment Agency (2006b). Drought prospects 2006 – August update.
Scope	The purpose of the report was to refine the EA'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 and 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 cooperation with the farmers. The water supply situation is reasonably good with reservoir levels close to normal. The improved situation is down to the success of water companies' actions: • Hosepipe bans, non-essential use bans and appeals to save water reduced demand by 5-15% • All companies have increased their leakage control activities and many should be below planned targets for the year. • Additional old boreholes have 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 through 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 successful and critical 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 autumn or whether any the recommended actions were followed after August.

Author/Title	Environment Agency (2008) Hydrological summary of the 2004-2006 drought
Scope	Summary of the 2004 – 2006 drought and how it affected the Thames Region of the EA
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 in the region, causing a drought period which covered two dry winters as well as a dry summer. The aquifers in the region are dependent 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 EA. By summer 2006, groundwater levels were either noticeably low or exceptionally low, according to Environment Agency classification. This in turn impacted upon 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 in place to mitigate any potential adverse impacts as a result of this. 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 in close scrutiny, with a number of associated stakeholders involved. Hosepipe bans were imposed including for the first time since 1990 in London. Drought Orders were applied for by Thames Water and Southern and East Surrey Water, with the former application being 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, since the high rainfall in the winter of 2006 replenished deficits in effective rainfall. Questions have been raised 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 was evident
Data Issues	
Comments	

Author/Title	South-West Water, 2007. Drought Plan
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 Plan (WRP).
Summary	SWW drought plan takes into account a wide variety of scenarios in accordance with the guidelines produced by the EA. These scenarios consider levels of demand, single and multi-season droughts as well as anticipated climate change. Wimbleball, Colliford and Roadford make up the three Strategic Supply Areas (SSAs) used by SWW 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 have been derived for each of the SSAs, dividing local and strategic reservoirs into different zones. They relate to the Level of Service used by SWW which details the possible frequency of drought management measures. The company's strategy in the management of its water resources is to firstly 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. However if drought conditions occur at one of the strategic sources then SWW may need to apply for a Drought Order. The time taken to implement each of the measures is also considered, for example drought orders take much longer to apply than hosepipe bans. Both demand side and supply side drought management options are detailed. 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 which may be stressed to those which have a more abundant supply. In the past, SWW has made extensive use of this option. Emergency abstractions Reduced compensation flows Reduced prescribed flows **Environmental impacts:** Surveillance and monitoring programmes will allow SWW 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, as it will allow comparison with long term statistics. Other indications are considered to determine low groundwater levels as it hard to predict these. **Communications plan:** this uses a phased approach. It will 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) which is sent to a number of relevant organisations.
Key Points	
Data Issues	
Comments	

Author/Title	Thames Water Utilities Ltd, Water Resources Act (1991). Application for an ordinary drought order – London. Statement of reasons.
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 they 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 said that this would be unacceptable in a major city such as London, due to adverse effects on the environment, society and the economy. The London WRZ gets 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 quickly declined. Groundwater contributes to the flows of the rivers meaning that these storage levels determine the availability of water resources to London. Lower levels lead to low river baseflows in spring, summer and autumn which will 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 then 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 implementation of 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 their Drought Prospects Update the Environment Agency recommended that Thames Water make this drought order application. Thames Water used their Water Resources Management System model to predict river flow levels. Hydrographs of a number of past droughts were plotted against that for 2006 with 50 per cent average rainfall as the scenario. River flows 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	Waterwise, 2006. Garden Watering Restrictions. A report to Defra reviewing international models of external water use restrictions, November 2006.
Scope	The report clarifies the aims 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 2004-06: • 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 have 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 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 I envisaged the clearer and more consistent restrictions will foster more understanding amongst consumers.
Key Points	Important to have consultation on the amendments in order to generate consensus amongst stakeholders.
Data Issues	
Comments	

Appendix B: Further information on case studies

Bedford Ouse at Offord, adapted from Catchment Spatial Information, National River Flow Archive, CEH (NERC, 2005).

Elevation			Geology		Land Use	
Min (m)	Max (m)	Weighted (m)	Type	Percentage	Type	Percentage
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

Exe at Thorverton, adapted from Catchment Spatial Information, National River Flow Archive, CEH (NERC, 2005).

Elevation			Geology		Land Use	
Min (m)	Max (m)	Weighted (m)	Type	Percentage	Type	Percentage
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

Appendix C: Drought metrics and re-constructed 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.

Such techniques have been widely used in the literature to establish the severity of droughts or periods of low flow (e.g. Cole & Marsh, 2006; Jones *et al.* 2006). 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 (for example, November – April). This is particularly useful in the context of the present study, as it permits 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 2-year and 3-year averages of successive winters are employed in this study.

Drought Severity Index

Bryant *et al.* (1992) developed a Drought Severity Index (DSI) based on accumulated rainfall or runoff deficiencies. Within this approach, monthly values are first expressed as an anomaly relative to a baseline period (e.g. Bryant *et al.,*1992, used the 1951 – 1980 means; Fowler & 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.* 1992 set this criterion to be three months of above average flow, and this approach was also applied to long rainfall records by Mawdsley *et al.* (1994) and to long reconstructed flow records by Jones & Lister (1998). Phillips & McGregor (1998) and Fowler & Kilsby (2002) used both 3- and 6-month termination criteria when examining water resources droughts in southwest England and Yorkshire respectively. In the present study, a 3-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, clearly 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 which employs a 'baseline' period against which to compare, the choice of period is also likely to be influential. Whilst 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 of termination criteria used.

Mawdsley *et al.* (1994) note that the measure should be used as an illustrative device rather than a strictly objective measure. However, accepting these caveats, the cumulative deficit index provides 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 (Fig 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, defined as the flow exceeded for 70 and 90 percent of the time. The threshold approach can be applied to daily or monthly data.

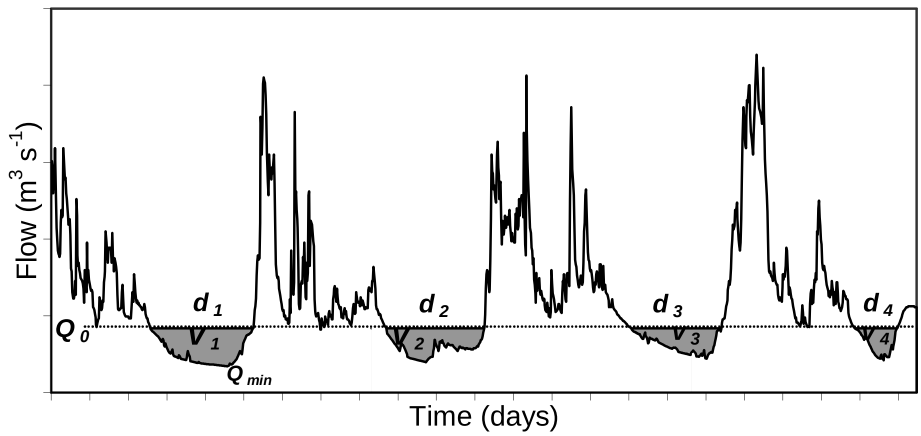


Figure C.1 Drought characteristics as defined by the threshold level method for daily time series (from Hisdal et al., 2004).

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 & 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.* 2009.

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 drought deficit indicator (e.g. Tallaksen et al, 1997). To calculate a deficiency timeseries 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, and 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. It should be noted that 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 timeseries returns to a level below the threshold (Hisdal *et al*., 2004).

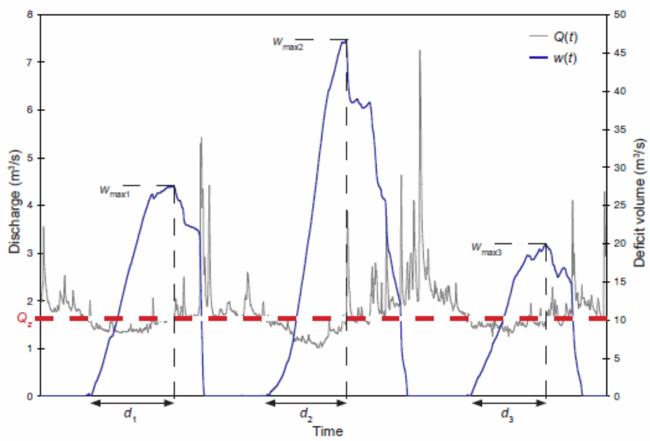


Figure C.2 definition of the deficit characteristics (d), and deficit volume (wmax) (from Fleig et al. 2006)

The SPA has a number of problems with which it is associated. Firstly, analyses performed on flow timeseries by SPA tend to highlight many very minor drought episodes (for example, events which last only one time step) regardless of the threshold level employed. A second significant problem with the SPA 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, the SPA is applied with a low threshold in order to minimise the time and deficit required to highlight multiple seasonal droughts in a timeseries (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. It 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 Standardized Precipitation Index (SPI) (McKee et al., 1993) is increasingly used as an indicator of meteorological drought. The SPI is being used in the EA project on the spatial coherence of UK and European droughts, and is described in the Lloyd-Hughes *et al.* 2009. The SPI 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.* 2009), and are based on gridded rainfall data. To allow an assessment at the two case study catchments, two time series were used, one for the South West UK, and one for 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 & Lister, 1998) were recently updated to 2002 (Jones *et al.* 2006). Reconstructed records on the Exe therefore extend from 1865 – 2002, whereas on the Ely Ouse, the record has been extended back to 1800 during the previous 'severe droughts' project (Wade *et al.* 2006).

The process of river flow reconstruction is described in detail in Jones (1984), and the updating of the records to 2002 by Jones *et al.* (2006) (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.* 2006), 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 rain gauge distribution is thought to be stable (Jones *et al.* 2006). A further issue is the assumption of constant actual evaporation employed by the model − whilst this is a reasonable assumption (see Jones *et al.* 2006), it may clearly be influential on modelled estimates, particularly for extremes like droughts.

In general, the reconstructed flows are highly indicative of historical river flows, and have achieved good modelled accuracy (including independent verifications) in published work (Jones & Lister, 1998; Jones *et al.* 2006, Jones *et al.* 2006a). 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 still 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 resource model

Summary

A spreadsheet model was developed to simulate Grafham's yield for the EA 'Long Droughts' research project workshop with Anglian Water on 2nd March 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.

Introduction

This note describes the set up of a simple Excel water resources model for Grafham reservoir that was developed for the 'Long Droughts' project workshop with the Environment Agency and Anglian Water.

The model has been set up based on a similar daily model, which was used in the previous EA '*Severe Droughts'* project and shown to produce identical results to OSAY, Anglian Water's own water resources system model.

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

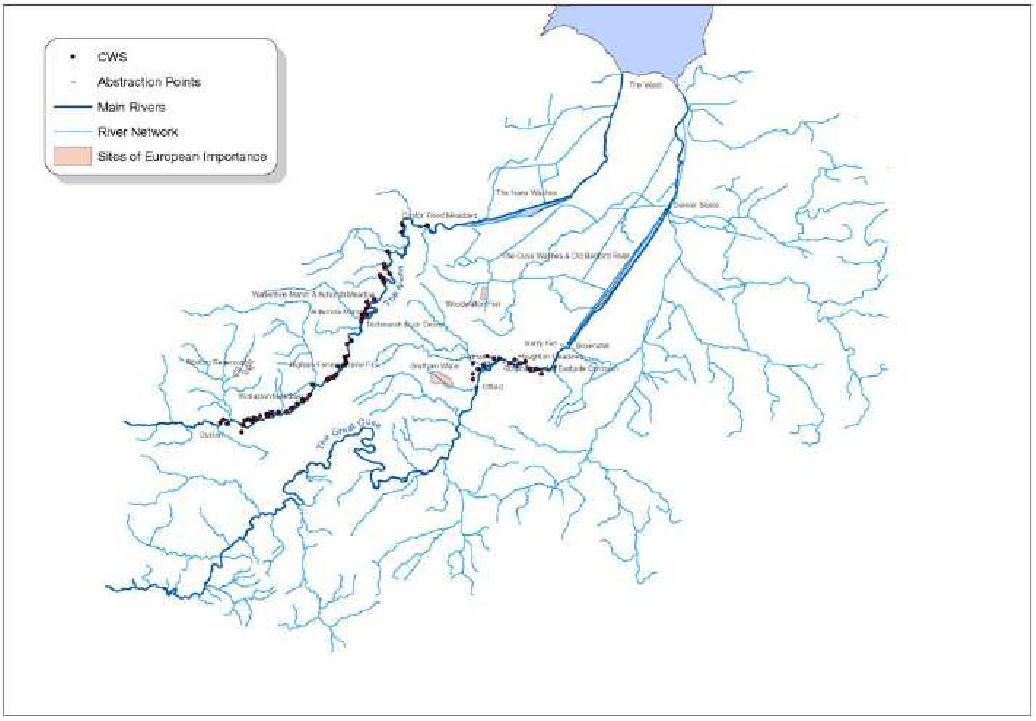


Figure D.1 Location of Grafham, abstraction points and sites indentified in 2006 Drought Monitoring Plan (WRc, 2006)

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 key parameters are summarised in Table 1 below.

Table 1. Grafham reservoir parameters

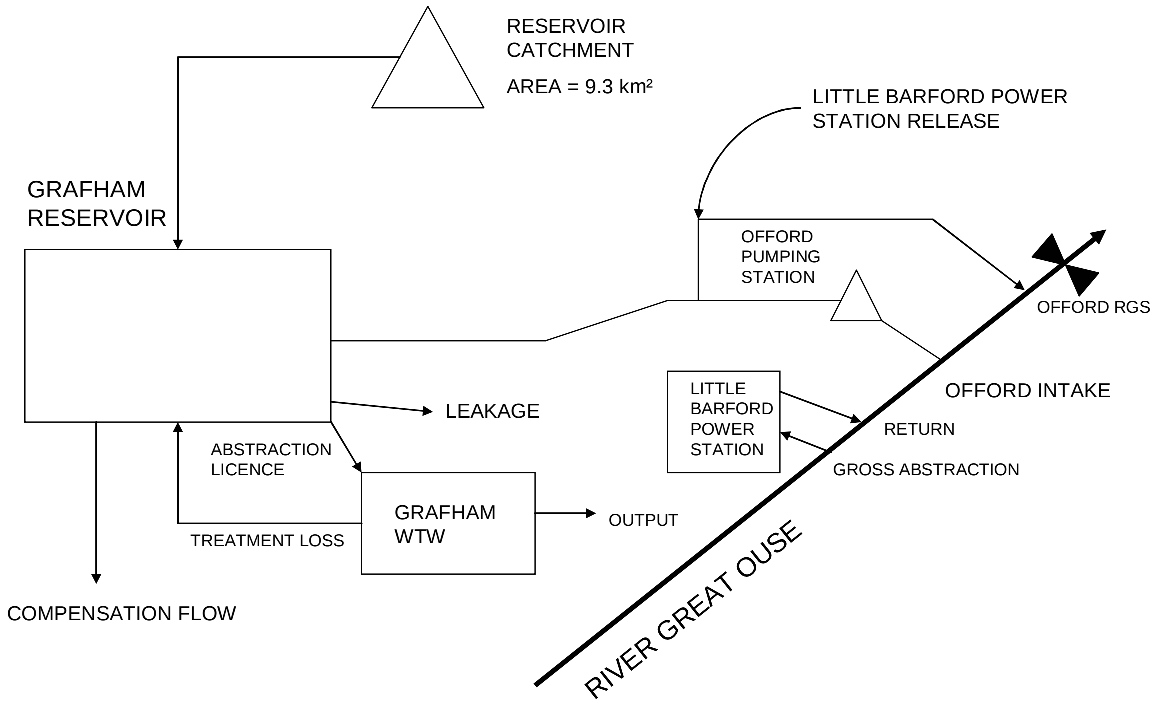
Key data		
Reservoir parameters	Value	Units
Pump capacity	485	Ml/d
Licence – max daily abstraction	485	Ml/d
Gross Volume	55494	Ml
Dead storage	2627	Ml
Emergency storage	30days x yield 52867	Ml
Net reservoir volume		Ml
Freshets/Compensation Flow	5.5	Ml/d
Target yield	245.0	Ml/d
Start volume	100%	
Minimum residual flow at abstraction point	136.00 – calculated : 136+0.25(flow-136) Ml/d	Ml/d

The following monthly demand factors are used:

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.

GRAFHAM SYSTEM SCHEMATIC (ADAPTED FROM AWS, 1997)



The model logic considers that:

- Water is available at Offord when flows are greater than the Minimum Residual Flow 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 and we have considered feedback from the company’s water resources team on an earlier draft table.

Table with drought measures

	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 key figures for Grafham's yield with no restrictions and simulated from 1920 are as follows (with critical years in brackets):

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 1970 & observed from 1970	238 Ml/d (1934/1976)*
Factored Flows	238 Ml/d (1922/1934)
Regression	300 Ml/d (1934/1922)

*If a target yield of 245 Ml/d is applied to the monthly model with combined factored & observed flows for Offord from 1970, the reservoir fails in both 1922 and 1976 for a total of 5 months.

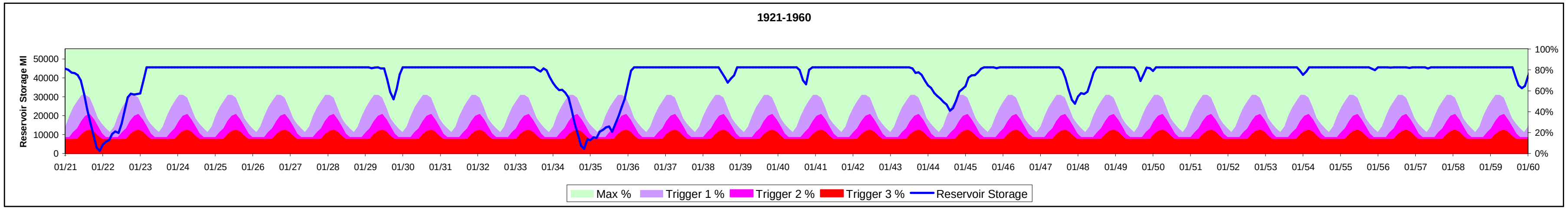
The spreadsheet modelling shows that the yield is highly sensitive to the choice of flows at Offord and influenced by switching from a daily to monthly time step. In addition the critical years of 1933/34, 1975/76 and 1922 are fairly close and switch order with different flow series.

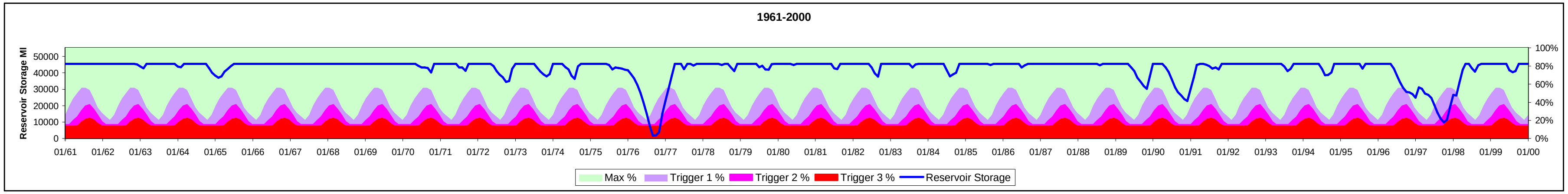
The factored flows produce the most realistic yield for Grafham and therefore these will be used for the workshop examples of long droughts.

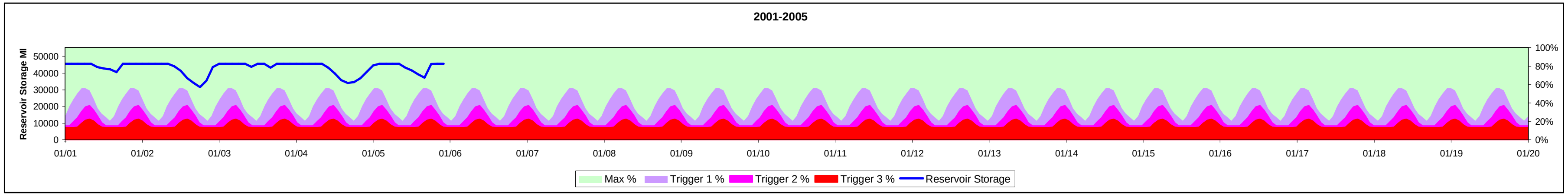
Example outputs of monthly model

Target Yield: 245 Ml/d

Scenario 1 (No Restrictions)







Flow series

Application of the previous 'Severe Droughts' project reconstructed flows led to a significantly higher yield for Grafham than Anglian Water's modelled flows. It was understood that this was due to a range of uncertainties in the modelling (both Anglian's and the research project's) and transposition of reconstructed flows from Denver to Offord where water is abstracted for Grafham.

This work was revisited as part of this study and the following river flow time series were reviewed:

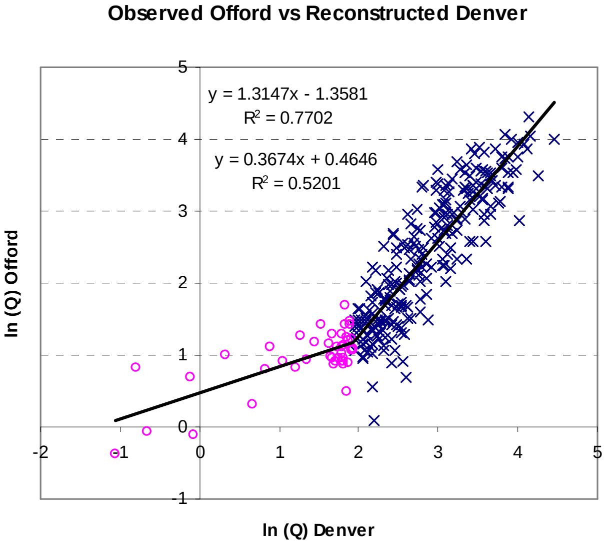
- Jones et al. (2006) reconstructions at Denver sluice and transposition to Offord
- Anglian Water's modelled flows from 1918 – 2003 based on the Stanford Watershed Model (SWM)
- Observed flows from Denver Sluice and Offord from the National Water Archive[4]

As a result two new records were constructed for Offord:

- Reconstructed Offord flows based on monthly flow factoring from 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%) but below this threshold the relationship was poor (r^2 55%)

This provided new reconstructed flows for this study that produced realistic yields. It was clear that further work could be completed (and would be beneficial) based on rainfall-runoff modelling using long term rainfall and temperature data sets at Offord but this was outside the scope of this study.

[4] Denver NWA record is patchy and incomplete – further data are needed from the EA to complete the record. .


Observed Offord vs Reconstructed Denver
y = 1.3147x - 1.3581
R2 = 0.7702
y = 0.3674x + 0.4646
R2 = 0.5201
ln (Q) Offord
ln (Q) Denver
5
4
3
2
1
0
-1
-2
-1
0
1
2
3
4
5

Appendix E: Wimbleball water resource model

Summary

A spreadsheet model was developed to simulate Wimbleball's yield for the EA 'Long Droughts' research project workshop with South West Water on 29th 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.

Introduction

This document describes the set up of a simple Excel water resources model for Wimbleball reservoir located in South West Water's (SWW) Wimbleball Strategic Supply Area (SSA) (Figure E.1). The model has been set up based on naturalised flow time series, licence and reservoir information provided by SWW.

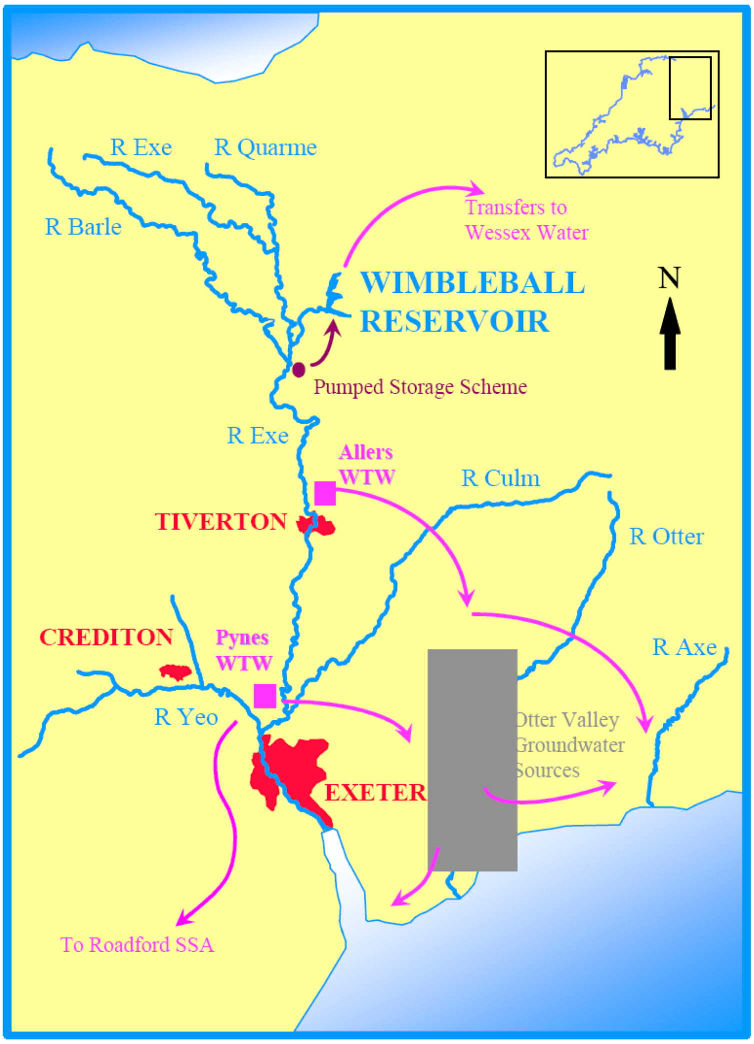


Figure E.1 Transfers and abstraction points for Wimbleball (Drought plan 2008)

Wimbleball reservoir

Wimbleball reservoir is mainly used for augmentation of river flows 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.2 (and licence information is listed in Table E.1).

Table E.1 Wimbleball Reservoir Pumped Storage licence data

Licences	Daily Licence (Ml/day)	Annual Licence (Ml)	Additional comments
Wimbleball PS	150	13633 (Jan-Dec)	Abstraction between 1st Nov and 31st Mar only
			Prescribed flow = 1.16 m3/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 shut down due to water quality.
Wimbleball release		12585	
River Exe at Northbridge Licence of Right (for Pynes WTW, Exeter)	24.457	8926.8	Licence of Right
River Exe at Northbridge (for Pynes WTW, Exeter)	42	14300	Prescribed flow = 3.16 m3/s at Thorverton GS (based on Thorverton natural flow)
River Exe at Bolham (for Allers WTW, Tiverton)	32	11564.5	When the natural flow in the R. Exe at Thorverton is 3.16 m3/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) have been constructed based on naturalised daily flows provided by SWW and a monthly flow re-construction by Phil Jones for Thorverton GS. Naturalised flows by SWW have been used from 1957-2006 and from 1865-1956 regression analysis was undertaken to construct flow records for Exebridge and Wimbleball based on Jones' Thorverton flows.

Linear regressions were undertaken using the daily flows provided by SWW and applying the correlations to Phil Jones data. The coefficients of determination R2 were between 0.97 and 0.98. A check on the re-constructed flows provided by Jones revealed a general underestimation of flow volume at Thorverton by app. 5% compared to flows provided by SWW and 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 SWW monthly flows directly with almost identical results.

Water resource model

In the model river flows at Exebridge intake and Thorverton are taken as the naturalised Exebridge and Thorverton flows. The available flow for abstraction at Exebridge is however somewhat lower due to fish farm abstraction upstream of the intake, which is taken into account in the model calculations as illustrated in the schematic.

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/day and allowance of 50% above pf.
- Compensation flow has been set to 9.1 Ml/day.
- The net reservoir volume available is 21320 Ml/day 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 March 31. It is assumed that abstraction occurs at a maximum rate of 150 Ml/day up to an annual maximum of 13666 Ml. Once the annual licence is reached no further abstraction can take place.
- Actual pumping is assumed to be 135 Ml/day rather than 150 Ml/day 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 SWW.
- 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 have been included with similar results: one based on Wessex demand and one taken from the WRP for Wimbleball SSA. The Wessex demand profile has been used in the final model.
- Surface water abstraction at Northbridge and Bolham is calculated based on flows at Thorverton. If naturalised flow drops below the prescribed flow abstraction is limited to 2.7 Ml/day plus 24.457 Ml/day 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/day.

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.[5]

- 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 and we have considered feedback from the company's water resources team on an earlier draft table.

[5] In Miser it is assumed that if the flow in the river rises above 1400 Ml/d, the intake is switched off for 2 days. However, if during these 2 days the level falls below 1400 Ml/d again, abstraction can commence immediately. If the river level rises above 2000 Ml/d, no abstraction can take place under any circumstances.

Table with drought measures (measures highlighted in pink not in plan - not considered acceptable measures)

	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
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		

Deployable output

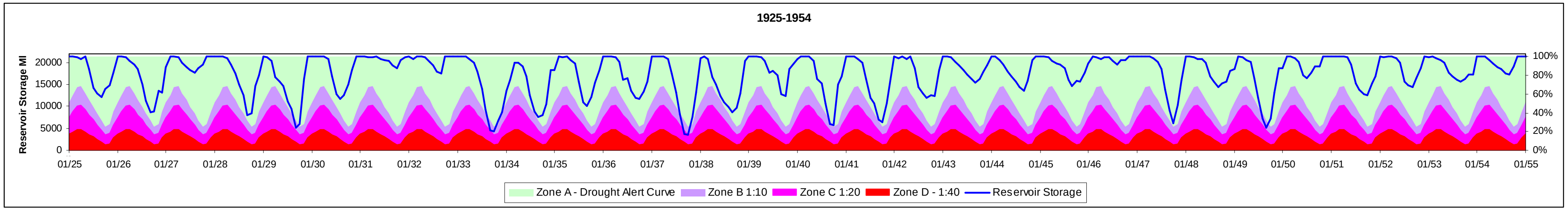
Based on the simplified model the DO has been assessed to app. 140 Ml/day for 1975-76, the design period used in SWW water resource plans which is slightly larger than the current maximum demand (WTW capacity and Wessex demand). This is based on a daily version of the model and it was found that the DO needed to be set somewhat higher to obtain a similar drawdown using a monthly time step.

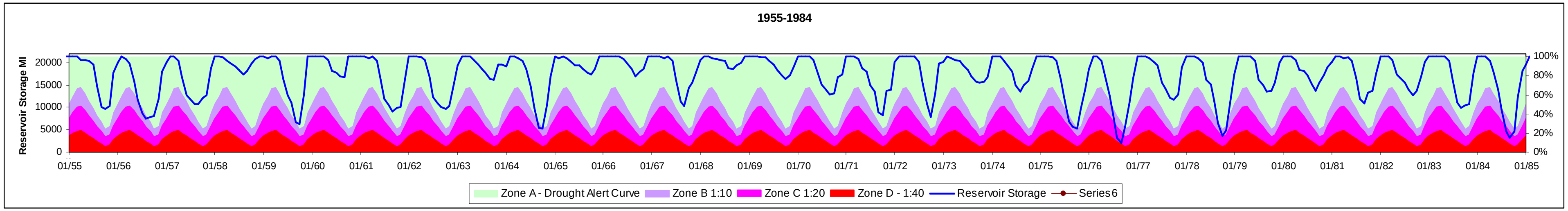
Consequently the model will be used with a target DO of 150-155 Ml/day for the workshop. The difference in drawdown is due to smoothing of flows and fish farm abstraction in the dry summer months.

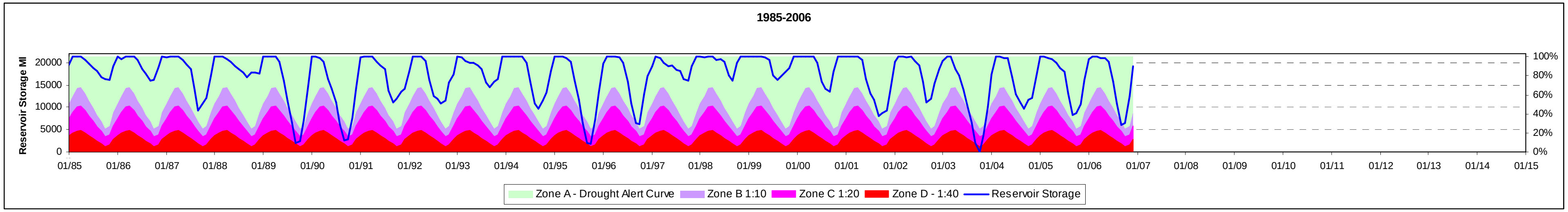
Example outputs of monthly model

Target Yield: 150 Ml/day

Historic scenarios







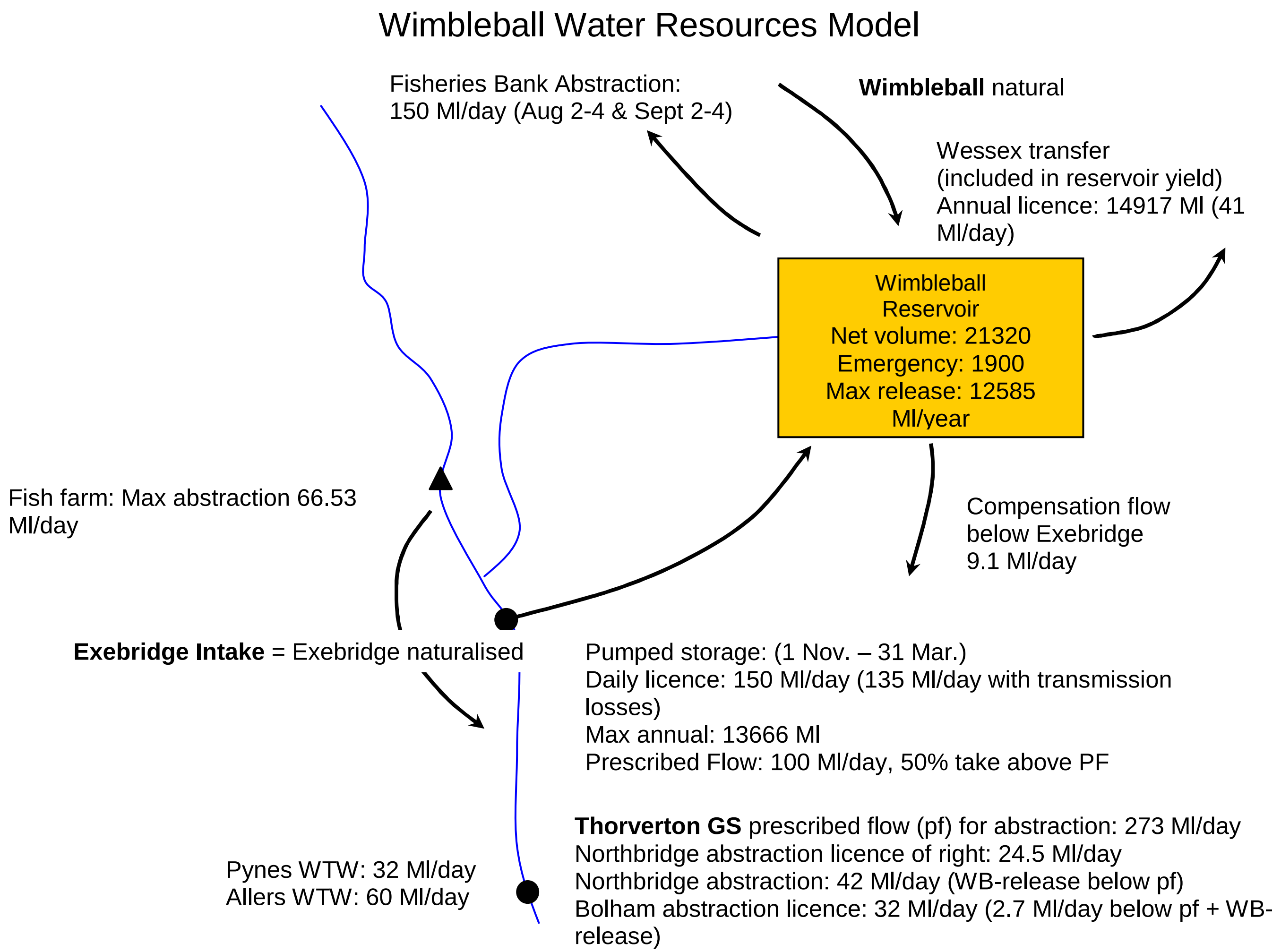


Figure E.2 Wimbleball reservoir schematic

Appendix F: Guidelines for hindcasting river flow and other climate records

Introduction

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. (2006) have shown that river flows may be reconstructed at the monthly scale, from the extensive rain-gauge network that is 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.

The purpose of this note is to provide some guidelines on climate reconstruction, particularly of areal rainfall and runoff records. Chapters 1-5 provide an overview of available data and description of different methods for extending hydrological data series. Chapter 1 considers rainfall, chapter 2 runoff, chapter 3 approaches to using neighbouring catchments where long records exist, chapter 4 extensions to the daily timescale, and chapter 5 considers ancillary variables such as temperature and evaporation. A step-by-step guide to extending and using river flow series for water resource and drought planning is included in section 6.

1. Rainfall records

The UK has the most extensive network of rainfall recording anywhere in the world. The digital network is maintained by the Meteorological Office (now in Exeter), and all the available daily data have been digitized since 1961. Earlier daily data have been digitized as a result of exercises such as the Flood Studies Report in 1975. A cursory look through the rainfall archives held at the Meteorological Office and a study of the annual volumes of British Rainfall (available from 1865 until publication ceased in 1991), however, indicates that before 1961 only a small subset of the potential data has been digitized. The paper rainfall archives (held at the Meteorological 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 have been developed between the 1860s and the 1970s. These records can be consulted, and have been used by many to develop long monthly records for individual locations or for large regions and the country as a whole (Jones, 1977, 1981, 1983, Tabony, 1980 and Wigley et al. 1984). It is these data sources that have been 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 digitized 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 Meteorological Office has developed daily and monthly gridded datasets (at 5 by 5km resolution) from the available digitized 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). 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.

Study of the number of stations used by Perry (2006) indicates that no extensive digitization exercises have been recently undertaken, and 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 by 5km grids in the software package EARWIG, developed for the EA by Kilsby et al. (2007). One advantage of using the Perry (2006) source is that the gridding uses elevation, 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. (2006) 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 (see Wright and Jones, 1982 and Jones et al., 1997 for some spatial maps of extents). There are plans at the Meteorological Office 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 digitization 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 possibility 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. (2006). 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 (percent changes, st-dev 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).

2. Runoff records

Runoff records have been reconstructed back to 1865 by Jones et al. (2006) for 15 catchments across England and Wales. A list of the catchments is given in Table F.1 (which has been modified from Jones et al., 2006). Their locations are shown in Figure F.1.

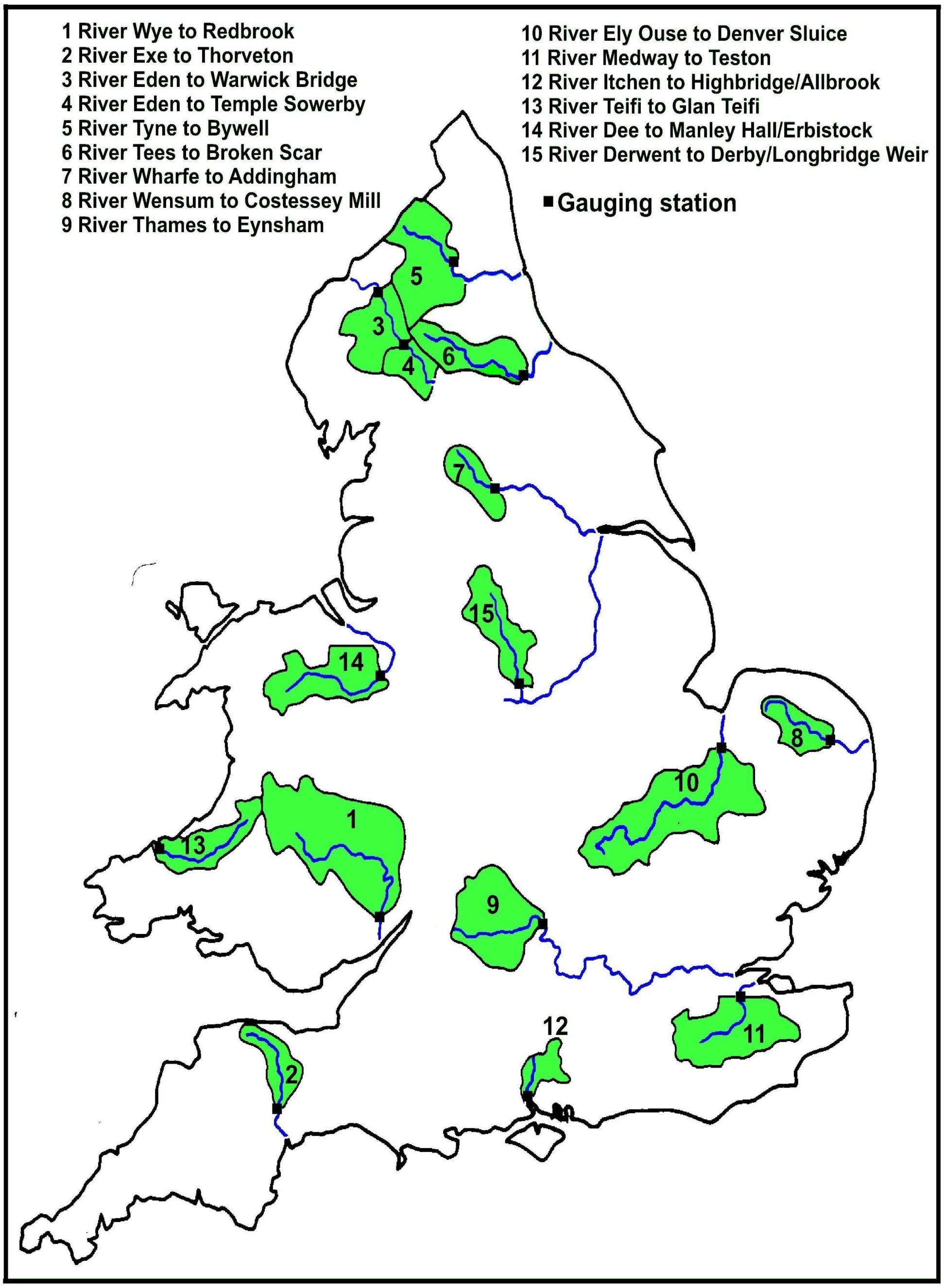


Figure F.1 Locations of the 15 catchments used in Jones *et al*. (2006).

Table F.1 Details relating to catchments, catchment observed-flow series (gauged and naturalised) and model calibration periods

Catchment	Flow gauge	NGR of gauge	Area (km^2)	1961-90 precip. (mm)	Ave. Flow (m^3s^{-1})	Observed flows (NRA) used in earlier work	Observed flows (EA) used for the updating	Naturalised flows used in the updating	Parameter calibration periods
Tyne	Bywell	45 (NZ) 038 617	2176	1015	45.2	1956-93	1956-2003	1956-1993	1962-1977
Tees	Broken Scar	45 (NZ) 259 137	818	1141	16.9	1956-93	1956-2003	1956-1993	1957-1971
Wharfe	Addingham	44 (SE) 092 494	427	1383	14.1	1962-93	1973-2003	1995-2000	1964-1977
Derwent	St.Mary's Bridge	43 (SK) 356 363	1054	1012	17.8	1977-93	1935-2003	1977-1997	1977-1993
Ely Ouse	Denver Complex	53 (TF) 588 010	3430	587	11.8	1926-93	1950-2003	1980-2002	1962-1977
Wensum	Costessey Mill	63 (TG) 177 128	571	672	4.0	1960-93	1960-2003		1964-1974
Thames	Eynsham	42 (SP) 445 087	1616	730	13.8	1954-93	1951-2003	1955-2003	1964-1976
Medway	Teston	51 (TQ) 708 530	1256	744	11.2	1957-94	1956-2003	1920-1996	1970-1993
Itchen	H.bridge+A.brook	41 (SU) 467 213	360	833	5.4	1959-88	1958-2003	1970-2000	1969-1988
Exe	Thorverton	21 (SS) 936 016	601	1248	16.3	1956-93	1956-2003		1958-1977
Wye	Redbrook	32 (SO) 528 110	4010	1011	74.3	1937-93	1936-2003		1956-1975
Teifi	Glan Teifi	22 (SN) 244 416	894	1382	28.9	1959-95	1959-2003		1971-1994
Dee	Manley Hall	33 (SJ) 348 415	1019	1369	31.2	1970-89	1937-2003	1969-2002	1970-1989
Eden1	Temple Sowerby	35 (NY) 605 283	616	1272	14.4	1965-93	1964-2003		1965-1977
Eden2	Great Corby	35 (NY) 470 567	1367	1146	34.0	1967-93	1959-2002		1967-1977

- All catchment data in Table F.1 originate from the Concise Register of Gauging stations (see www.nwl.ac.uk/ih/nrfa/station_summaries/crg.html)
- Some values are period specific and will differ slightly from statistics given elsewhere
- Flow data (for updating) originate from Environment Agency (EA) and Centre for Ecology and Hydrology (CEH) sources
- There are known problems with the gauging of high flows on the Thames, Dee and Eden1
- Rating changes will/have affect(ed) observed flow series on the Wharfe, Wye, Eden1 and Eden2
- Naturalisation methods have changed with potentially adverse consequences for reconstructions using original model parameters on the Medway and Itchen
- There are doubts as to the homogeneity of observed flow series for the Ely Ouse
- The gauged flows for the Wensum have been affected by significant abstractions, just upstream of the flow gauge, since 1988
- Naturalised flows were used for original model calibrations and (where possible) validations on the Derwent, Wensum, Medway, Itchen, and Dee
- There are significant periods of missing data within the naturalised flow series for the Tyne and Tees

Further details of catchment characteristics, observed and naturalised flow series and calibration/validation exercises can be found in Jones and Lister (1997 and 1998) and Jones *et al.* (2006)

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 (see Wright, 1978, for full details). 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. In addition, it is 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., 2006).

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) having been derived by Wright (1978), based on simple water balance assumptions. The use of the same twelve 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 e.g. Jones et al., 2006). It also saves considerable effort in developing long series of potential evapotranspiration for each catchment. Figure F.2 shows the reconstructions of flows for the 1907-11 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 imply that changes in land use across the 15 catchments have had a negligible effect on long-term flow statistics.

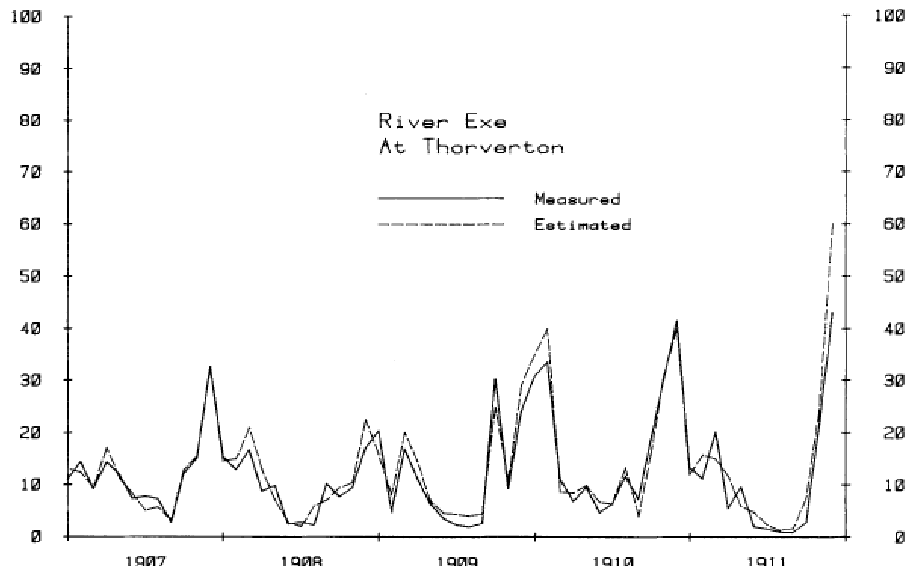


Figure F.2 Reconstructed and measured river flow on the River Exe from 1907-1911

3. 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 1961-90 average has shown that the baseflow index 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.

4. Extensions to the daily timescale

Almost all water companies have complex models of their river and water resource 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, an earlier EA-funded study (Jones et al., 2006 and 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 resource 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. (2006) provides a step-by-step guide of the process to develop the necessary input data for a resource model.

5. 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 by 5km gridded sources discussed earlier (Perry and Hollis, 2005a, b and Perry, 2006). Examples of the approach are given in Jones et al. (2006) and Wade et al. (2006).

6. Step-by-step guide to extending hydrological data

In the following a step-by-step guide has been produced based on the available data and methods described in the previous sections. Two methods, which could be used for extending hydrological data series using the reconstructed data series and undertaking water resource modelling, are described below:

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 as input for water resource 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. This will however require model calibration/validation that 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 that are shown to vulnerable to extended droughts.

Method 2: River flow reconstructions from other river flow series

A simpler approach is to develop river flows series for use in water resource models directly from Jones' monthly river flow reconstruction records using regression methods. River flows from the nearest gauge with similar hydrological and hydro-geological settings are used along with factors or regressions to hindcast monthly flow records.

Both methods may require conversion from the monthly to daily time scale for use in water resource models. However, we have shown (Wade et al., 2006) 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 (Section 4).

Each of the two methods is 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 ET) for the 15 catchments in Figure F.1 and 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 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. The baseflow index 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.

1. **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. Wade and Vidal, 2007; Moore *et al*., 2007; Jones *et al*., 2006; UKWIR, 1997; Bloomfield *et al*., 1997).

        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 (for example 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 PE 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 Section 5 above).

2. **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 resource modelling.

    A monthly conceptual or statistical model may be appropriate for many applications, e.g. estimating changes in recharge. As in Jones et al., 2006, 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.

3. **Use modelled monthly or daily river flows in water resource modelling (DO assessments and Levels of Service).** Re-constructed naturalised monthly or daily flow series are prepared from the rainfall-runoff model results and used as input for water resource 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 Figure F.1 and 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 web-site (Landis web-site http://www.landis.org.uk/gateway) and the Hydrometric Register and Statistics 1996-2000 (CEH 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 resource 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 percent change, stdev 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 resource 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 4a above.
4. Use reconstructed monthly or daily river flows in water resource modelling (DO assessments and Levels of Service). Reconstructed naturalised monthly or daily flow series are prepared and used as input for water resource models.

Appendix G: Guidelines for conducting drought workshops

1. Background

These pages provide guidance and suggest things to consider when developing exercises for workshops aimed at testing the resilience of water resource 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 solely covers the workshop design.

The workshop exercise described in the following is based on a strategy game approach. Strategy games have been applied in many different situations (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 scenario may 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 but in a workshop setting you have the added advantage that you can hear and respond to different views and get an immediate reaction to an intervention and it is through these interactions 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 enough, for a one day workshop, to simply get a response to the hydrological and water resource model data as it emerges and rely on the experience of the participants for the meaning of this for the work of the Environment Agency, Defra and the implications for the public. Inevitably there will be a balance between the advantages of a very detailed exercise and resources available to undertake it.

Ideally it would be beneficial to have representatives from the main the 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. the media, the public, special interest groups to include other important influences on decision making, either having live representatives of those 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. However 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 done by a water company staff member in role. It is recommended that a representative of the regional EA to be present if at all possible.

2. 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 resource model review;
- Analysis of available climate and hydrological data for identification of drought periods and assessment of water resource vulnerability to drought;
- Development of new water resource 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 resource modelling;
- Review of water company drought plans and identification of drought measures previously used for managing drought;
- Further data collation on environmental impacts.

A week in advance of the day a brief agenda should be sent out to the workshop participants. This should be sufficient to map out the beginning and ending times and 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 it emerges.

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

As the workshop depends a lot on interactions in the moment some thought has to be put into how these should be recorded in a way that doesn't require too much time consuming transcription afterwards. Clearly how this is done is up to the people involved. What follows is a list of the devices used in this "Impacts of long droughts on water resources" study (some of which are described in more detail below):

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

Template for interventions

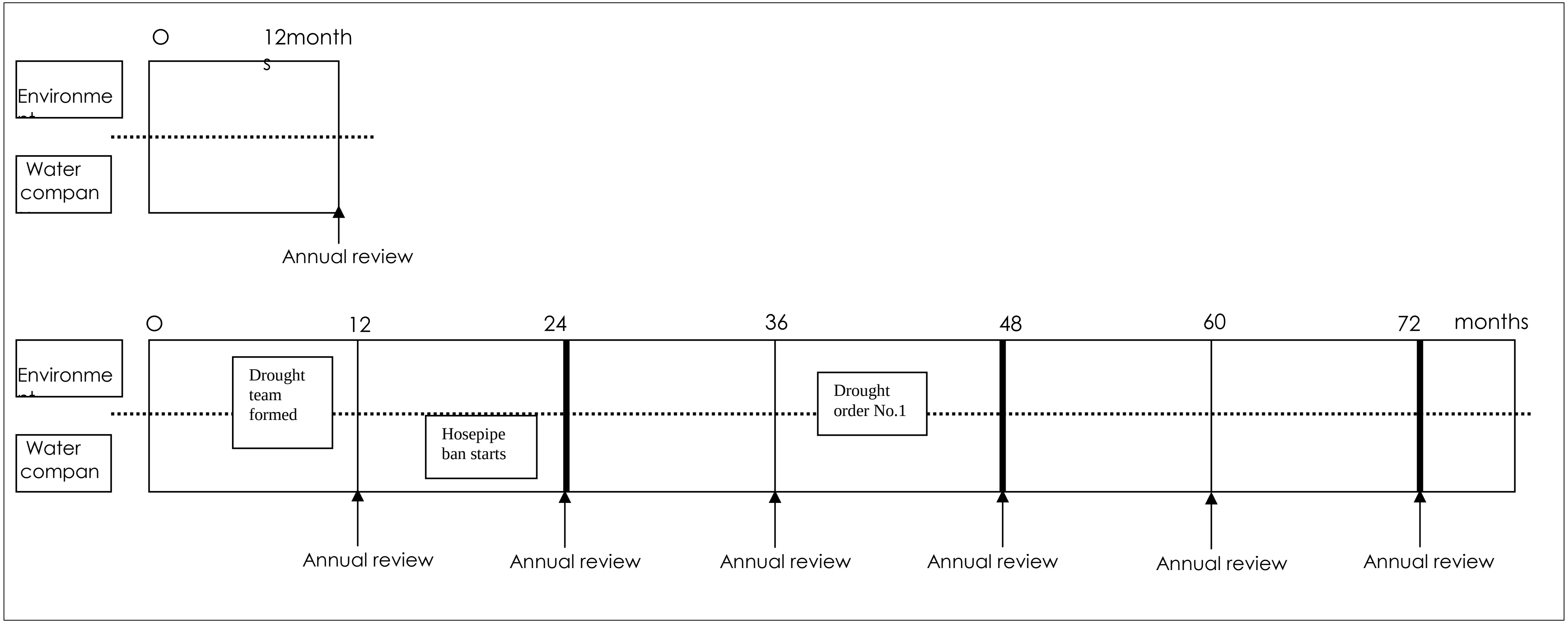
This captures how particular decisions are made during the game. It is intended to be a quick way to pick up the key points in a way that doesn't significantly interrupt the flow of the discussion and the unfurling of the scenario. A template as below can be used to provide a check list of questions to be loosely followed:

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:	

Time line of interventions

A time line 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 (1 sheet is 12 months). Each annual sheet is added to the earlier sheet to create the whole time line.

This visual representation is then available for the Annual Review process.



Emerging time line of actions captured on flip chart paper

Template for annual reviews

Annual templates (as below) can be completed by a member of the facilitation team and they can then form the structure of the report by the water company to Defra and the Environment Agency.

After the water company had reported their concerns and actions then the EA and Defra has the opportunity to give their own reflections on the year and ask challenging questions to the water company.

WIMBLEBALL: SCENARIO ONE	
Year One 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: e.g. *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 happens at the end of each of the scenarios. Many of the questions for this debrief will emerge through the exercise although some can be anticipated. This is an opportunity to reflect on what happened during the game and what was surprising or interesting of relevance to drought management planning activities in the water company and the consequence of this for the EA and Defra. The aim is to stand back a little from detailed content questions, although there may be some of this for the sake of clarification, and ask questions for reflection on the action taken e.g.

Looking at your performance targets over the 4 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?

A member of the facilitation team takes notes on what was said which 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 and ask whether these are sufficient or if there are changes to be made to make them more efficient in the event of a long drought. This is also an opportunity to discuss the strengths and weaknesses of the scenario game and how plausibly it represents the real world.

3. 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 both a water company and an EA 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-its) that go on the time line. 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.

In addition to focussing on the content of the scenarios there should also be a wider discussion of the approach that enables participants to discuss the plausibility of the exercise and how easy is it to look at the future like this.

4. 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 asking 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. After this the findings of the exercise could be presented in a feedback workshop to highlight key issues or areas for change arising from the exercise.

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Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

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Environment Agency
Rio House
Waterside Drive, Aztec West
Almondsbury, Bristol BS32 4UD
Tel: 0870 8506506
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk