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Testing the resilience of water supply systems to long droughts

Short Title: Testing drought resilience

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Abstract

Public water supply systems are designed to maintain water supply through extended periods of dry weather without excessive cost or environmental damage. During a drought, water suppliers can take further measures to enhance supplies or reduce demand. The introduction of drought measures is usually formalised in a drought plan, but there is often little evidence that the plan will prove successful during a range of feasible droughts. As the climate changes, recent hydrological data may be a poor guide to future drought, and planned actions may prove insufficient to maintain adequate water supplies.

This paper describes a method for testing the resilience of water company drought plans to droughts that are outside recent hydrological experience. Long severe droughts of the nineteenth century provide an opportunity to test water supply system behaviour in a range of realistic droughts. The method developed combines system modelling with an interactive approach that asks water system managers to work through the actions that they would take at different stages of the drought, without knowledge of subsequent drought development.

The approach was tested for two contrasting English water resource systems. In both cases, the existing water supply and drought planning measures succeeded in maintaining water supply, but significant demand restrictions and engineering measures had to be introduced. Wider use of the method by water supply planners should allow the refinement of drought and water supply plans, and will also create increased awareness of the actions necessary to manage a range of droughts.

Keywords

drought, planning, climate change, river flows, water supply, reservoir modelling

1. Introduction

Public water supply systems are designed to smooth the natural variability of climate and hydrological response so that a reliable water supply can be maintained through a very wide range of weather conditions. It is generally neither practical or affordable to provide unlimited water through any possible drought, so water supply systems are usually planned to meet a design standard. The standard may be expressed as a return period: for example, a system may be designed to maintain supplies without restriction through a drought with a return period of 1 in 50 years. This is analogous to the approach widely used for flood scheme design (for example, MAFF 2001) but its application to extended droughts presents a number of difficulties. Droughts can be classified by their magnitude (dryness) and duration, but the sequencing of drier and wetter periods within a drought can be very important for the performance of water supply systems. This means that two droughts with the same metrics (return period, duration, magnitude) could lead to different outcomes in the same water supply system. Short droughts (perhaps six to nine months) usually present few problems for water supply: long droughts lasting a year or more are much more testing because they usually include dry winters, which reduce the replenishment of groundwater and reservoirs, placing them under greater stress in the following summer.

There is limited hydrological data for historic droughts in the UK. Most river flow records are relatively short: with the majority of the gauging network established in the 1960s (Marsh and Hannaford 2008), few records exceed 50 years. In this period there have been very few long droughts: in the UK, major droughts since 1950 are 1959, 1976, 1990-92, 1995-97 and 2004-2006 (Marsh et al 2007). Even these droughts were not experienced equally everywhere: for example, 2004-06 had the greatest impact in south-east England.

The paucity of reliable data on historical long droughts and the lack of experience of the way that a given system will respond means that all water supply planning is subject to a degree of uncertainty. The design standard will never be completely unambiguous: if a system is designed against a specific historic drought, system performance during equivalent, but different, future droughts cannot be guaranteed. If the system is designed against a synthetic drought of a calculated magnitude and duration, performance during real droughts will not be certain. In addition, there remains the possibility of a future drought that is beyond the design standard of the system. Further, as the climate changes, past droughts may become an increasingly poor guide to future drought: as global temperatures rise, evapotranspiration is expected to increase almost everywhere (Bates et al 2008), which is likely to have the greatest impact on low flows (Kay and Davies 2008). Climate change projections for the UK suggest significant decreases in average summer rainfall through the 21st century (Murphy et al 2009). Modelling the persistence of long droughts remains a problem for global climate models, but studies suggest that short droughts with a duration of 6 to 18 months will increase in frequency as the climate changes (Burke et al 2010).

Drought is recognised as an increasing problem in Europe. The drought of 2003 covered a third of the EU, affected 100 million people and cost 8.7 billion euros (Commission of the European Communities 2007). In England and Wales, water supply companies have a statutory duty under the Water Industry Act 1991 to prepare and maintain separate water supply plans and drought plans. Water supply plans have a 25-year horizon and aim to maintain supply through a repeat of the worst droughts of the twentieth century without significant restrictions on water use (Environment Agency 2008). Drought plans describe how the water company will monitor the onset of drought, forecast system performance and take steps to manage water supply, while avoiding serious restrictions on water use and unnecessary damage to the water environment (Environment Agency 2005). Taken together, the two sets of plans are intended to make sure that water suppliers are ready for the next drought, whenever it starts.

The theoretical basis for linking long-term water supply plans with short-term drought management plans is sensible and reflects good practice internationally (Wilhite 1991, Wilhite et al 2000). However, this theoretical strength does not guarantee that water supply systems will operate optimally through future droughts. There are two main areas of uncertainty: the resilience of the system itself to future droughts, and the appropriateness and timeliness of the actions in the plan.

It is likely that future droughts will be different from those of the twentieth century on which this system is based: for example, in the twentieth century, droughts in England and Wales typically lasted no more than two years, while several nineteenth century droughts were of much longer duration, principally as a result of clustering of periods of below average winter rainfall (Jones et al 2006, Marsh et al 2007). While water companies design their plans based on past experience, there is little testing to find out whether the actions in the plan will be sufficient to avoid unnecessary restrictions on water supply and damage to the water environment.

This paper tests the water supply and drought planning system on two example supply systems. A novel approach engages water supply managers directly in the testing, asking them to respond to a developing drought without prior knowledge of its magnitude or duration. In taking this approach, it is recognised that the water supply system consists not only of physical infrastructure but also includes the institutions involved in managing water supply and the people who act in this system both as managers and users of water (Sofoulis 2005). The paper describes the testing methodology (section 2), the characterisation of appropriate long droughts (section 3), water supply system modelling (section 4), the interactive workshops (section 5) and findings from the study (section 6). We draw on case studies from the UK, but the methods described are relevant to a wide range of water supply systems in other parts of Europe and the rest of the world.

2. Methodology and selection of case studies

This study assesses the resilience of the entire water supply system to drought, considering both the physical infrastructure and the adaptive actions that water supply managers and water users take during a drought. Water supply system simulation models are often used to test system operation, but can only reflect the rules that are built into the model. While some models are very flexible and allow for complex operational rules, this approach assumes that these rules can be designed fully before the drought and that they will be followed perfectly. Experience from previous droughts (e.g. Doornkamp et al 1980, Environment Agency 2006) shows that flexibility in decision-making is an important part of successful drought management. It is also clear that factors beyond objective hydrological measures of the state of the water supply system can be important in determining the actions that are taken. For example, it is hard to introduce demand saving measures during even a brief wet interlude in an otherwise dry year, and some water companies may be nervous about the juxtaposition of customer restrictions and the reporting of financial results.

The approach described here addresses the complexity of drought management by allowing management intervention in the supply system. Effective water supply management contributes to the robustness of the supply system: good management should help to delay or avoid entirely the worst effects of drought, while poor management may hasten supply failure and environmental damage.

In many respects this approach is similar to a traditional modelling approach to water supply system optimisation. Appropriate hydrological data is assembled (section 3), a suitable system simulation model is built and tested (section 4), system performance metrics are chosen, and simulation model runs are carried out to test system performance (section 5). In this study, though, the model runs consist not only of computer simulations but also include month by month interventions from the people involved in managing the system.

For this study two case studies were selected to test the resilience of different types of water supply systems to long drought. The criteria applied in the choice of the two study areas were:

- to consider sites that demonstrated different hydrological characteristics and consequently different responses to long droughts;
- to include water resources zones with reservoirs with a different balance of pumped storage and natural inflows;
- the availability of good quality, long time series of hydrological data and effective system models; and
- co-operation from water companies to make sure that drought management interventions could be represented accurately.

Many English water supply systems meet these criteria, but the two case studies selected were Anglian Water's Grafham Reservoir, and South West Water's Wimbleball Reservoir (figure 1). Both have been the subject of previous research (for Grafham, Cole and Marsh, 2006; Jones et al, 2006, 2006a; Wade et al., 2006; for Wimbleball, Lopez, et al., 2009).

Both of these case studies are in the south of England, but there are distinct differences. Grafham, on the Bedford Ouse in eastern England, 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. The Bedford Ouse has a mixed geology that includes impermeable glacial clays as well as chalk and limestone aquifers. Wimbleball is situated in the Exe catchment in south west England, with annual rainfall of nearly 1300 mm and lower actual evaporation than the Bedford Ouse. As a result, surface water runoff per unit area is around eight times higher in the Exe than the Ouse. The Exe catchment is mainly on impermeable sandstones. Other catchment characteristics are provided in Table 1.

Both Grafham and Wimbleball impound tributaries of the main river. Grafham has a net storage volume of about 55 million m^3 with a small natural catchment of 9.5 km^2. Most of Grafham's water is pumped from the Bedford Ouse at Offord, with a catchment area of 2600 km^2. Pumping is permitted at any time of year as long as flow is greater than 1.57 m^3 s^{-1}. A quarter of the flow above 1.57 m^3 s^{-1} must be left in the river. The maximum rate of pumping is 5.61 m^3 s^{-1}. There is a small compensation release from the reservoir of

0.06 m^3 s^{-1}. The deployable output of Grafham is about 250 Ml d^{-1}. Grafham is one of the three reservoirs in Anglian Water's "Ruthamford" system (the others are Rutland and Pitsford). This is Anglian Water's largest resource zone, supplying 1.5 million people across the west of the company's region, including the cities of Peterborough and Northampton.

Wimbleball has a net storage volume of just over 21 million m^3 and a natural catchment of 21 km^2 on the River Haddeo. Fill from this natural catchment can be augmented by pumping from the River Exe at Exebridge. Pumping is allowed only in winter (1 November to 31 March) and when river flow is above 1.16 m^3 s^{-1}. Half of the flow above 1.16 m^3 s^{-1} must be left in the river, and the maximum pumping rate is 1.74 m^3 s^{-1}. Wimbleball is mainly used to make releases to augment the River Exe for subsequent abstraction at Tiverton and Exeter. There is also a small direct abstraction by Wessex Water for parts of Somerset. The deployable output of Wimbleball is around 140 Ml d^{-1}. Wimbleball is the main source of water in South West Water's Wimbleball zone, supplying a resident population of about 340,000 people in East Devon, including the city of Exeter. Tourism is an important part of the economy of Devon, and peak demand reflects the large number of holidaymakers in the summer months.

These contrasting systems provide a good basis for testing drought planning and management. The catchments exhibit different responses to rainfall: Wimbleball's catchment is relatively flashy, while Grafham's large catchment responds more slowly to rainfall. The reservoirs are filled and operated in different ways: Wimbleball is an augmented impounding reservoir, while Grafham's small natural catchment means that it relies entirely on pumped storage. This means that testing drought management in these systems provides a good range of possible responses and allows more general conclusions about drought management to be drawn.

3. Characterising long droughts

3.1 Definitions of long drought

There is no widely-used definition for 'long drought' in the UK. Previous authors have drawn a distinction between short (8 – 10 month) duration droughts, which have the greatest effect on upland areas, and long duration (18 months plus) droughts, which have the greatest impact on southern England, where replenishment of reservoirs and groundwater recharge in winter is critical for water resources (Jones *et al.* 1998). Other work, undertaken to catalogue major historical drought episodes in England and Wales (Marsh *et al.* 2007), noted a repeated tendency for dry years to cluster together, resulting in multi-year droughts which tend to have the greatest impact on water resources. For this study, a long drought is defined as lasting two or more years, generally (but not necessarily) resulting from a succession of dry winters.

This section identifies historical long droughts in the two study areas by applying a series of widely-used drought metrics. While previous authors have catalogued major droughts in England and Wales (Marsh *et al*. 2007), these studies did not focus on long periods of deficiency, so major droughts thus identified are often relatively short. The 1975-76 drought, for example, is considered the benchmark major drought in lowland England, but would not meet the current definition of being a long drought. To be suitable for further examination in the workshops, it would also be expected that the long droughts identified should be spatially extensive, and associated with well-documented major societal and/or environmental impacts, so this section briefly considers the impacts and geographical extent of the identified drought events.

3.2 Reconstructed river flow records

There are few long droughts in the gauged flow records for either the Exe or the Bedford Ouse. Flow gauging on the Exe started in the late 1950s. While the Offord flow record starts only in the early 1970s, there is a longer gauged record from further downstream at Denver: reliable flow records available from the late 1950s, but there is a longer record from the mid 1920s. Jones et al (2006a and b) reconstructed flows for both the Exe at Thorverton and the Ely Ouse at Denver back to 1865 using the monthly statistical model of Wright (1978). This uses monthly rainfall records and long-term average evaporation. Wade et al (2006) extended the Ely Ouse record back to 1800 using the same methods. Jones et al (2006a p20) identify possible sources of error in these reconstructed records as:

- the use of constant monthly values for evapotranspiration losses;
- the potential for snowpacks to build up in winter periods;
- possible modification of the regression relationships through time due to factors such as changes in land use;
- changes in the locations and numbers of raingauges in the catchments.

For drought planning, ignoring catchment change is reasonable, as water companies are interested in the current response to long droughts. The other sources of error are important, but validation against long records demonstrates that the monthly flows are sufficiently reliable for testing the effects of long droughts on water supply.

In the reservoir modelling (section 4) the extended record for the Exe can be used directly in Wimbleball simulation. For Grafham, a regression relationship between Offord and Denver has been constructed (figure 2). For detailed reconstruction of daily river flows at Offord, more work would be necessary. One problem is that summer Denver flows are often zero, as downstream of Offord water leaves the main channel and enters the low-lying Fens. It would not usually be possible to pump water into Grafham during these periods, because of the abstraction licence conditions, so errors in very low flows are less important in reservoir simulation. The identification of appropriate long droughts below uses the reconstructed Denver (Ely Ouse) record.

3.3 Identification of long droughts using drought metrics

There is an extensive range of existing drought indicators reported across the literature (Hisdal *et al.* 2004 provide a review of some of the widely used drought characterisation techniques) and no single methodology for assessing drought severity is likely to reflect the full range of drought impacts. In this section three separate indicators, which capture drought severity in different ways, are used to examine long droughts in the study catchments.

A simple, widely used technique for examining drought sequences is relative ranking of *n*-month rainfall or runoff deficiencies. Table 2 shows the ranked 36-month and 6-month (3- and 5-year) non-overlapping runoff deficiencies for the study catchments. A notable feature of the results is the prevalence of events from the 19th century and early 20th century. For the Ely Ouse, over both the 3- and 5-year timescale, the four greatest deficiencies are from before 1910. Particularly notable are the two 36-month deficiencies in the 1802 – 1808 period and the two 36-month deficiencies between 1893 and 1903. While the relative ranking of the deficiencies is different in the Exe series, many of the episodes identified correspond to similar major drought episodes.

Whilst the *n*-month deficiency method provides a relative ranking of dry periods, it does not permit the identification of a discrete drought event with a defined duration. A widely used methodology (e.g. Hisdal *et al.* 2001; Fleig *et al.* 2006) is the threshold level approach, where the start and end of a drought is defined by a period when streamflow is below a certain threshold (normally defined as a flow exceedance value e.g. Q90 or Q70, the flow exceeded 90% or 70% of the time respectively), and drought characteristics thus derived include drought duration and deficit volume. 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; below-threshold events therefore rarely extend over a number of seasons, except on very permeable catchments. An alternative approach, which applies a different Q70 threshold for each month of the year and thus allows multi-season droughts to be captured, was used in this study (Table 3). 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 short duration, generally within-year, deficiencies, as the higher flow variability in this catchment prevents long-duration deficiencies from developing.

Bryant *et al.* (1992) developed a Drought Severity Index (DSI) based on accumulated rainfall or runoff deficiencies. Monthly values are first expressed as an anomaly relative to a baseline period. 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 until some termination criterion is reached (this was set to be three months of above average flow, in line with previous work: Bryant *et al.* 1992; Mawdsley *et al.*, 1994; Phillips & McGregor, 1998; Fowler & Kilsby, 2002). Results for the Exe catchment highlight similar events to threshold methods, and they are of relatively short duration (not shown; see von Christierson et al. (2009) for details). The DSI extending back to 1803 for the Ely Ouse (figure 3) demonstrates that the method identifies the main droughts selected using *n*-month deficiencies and threshold techniques, although the termination criteria are clearly influential: 1802 – 1810 becomes one long drought on the Ely Ouse. 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. Figure 3 also illustrates the DSI time series for a long groundwater level record (Therfield Rectory) from the Chalk, in the headwaters of the Ely Ouse catchment. 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).

3.4 Selection of long drought episodes for analysis

The long droughts identified in section 3.3 for the Ely Ouse and Exe generally correspond to major drought episodes in England and Wales from 1850, as characterised in Table 2 of Marsh *et al* (2007). Differences in the relative rankings of events between the two catchments partly reflect the regional nature of some of the major droughts. For example, 1887 – 1888 ranks highly on the Exe, but does not feature in the Ely Ouse table; Marsh *et al* 2007 note this was a surface water drought with the greatest impact in western Britain. Furthermore, the two catchments display contrasting drought characteristics, as a result of the different geological storages and precipitation regimes. The Exe is not as vulnerable to protracted deficiencies; while the 1887 – 1889 period has the lowest 3-year rainfall, this event does not rank as highly in terms of flow deficit, as a result of wetter interludes where flows were above the threshold. In contrast, the shorter but intense 1921 – 22 drought has the highest duration deficit volume, but does not feature in the top ten 3-month deficiencies. This implies that long droughts with shorter, intense interludes may be of the greatest significance in the Exe catchment, and suggests that the selection of events should focus on droughts with notable long-term (3-year) deficiencies, combined with a high ranking deficit below the low flow threshold.

The long droughts identified in this analysis present a number of possibilities for case study events for the workshops. Some of the droughts occurred relatively recently, so water supply managers will have contemporary experience of handling them; droughts from the 1960s onwards are therefore rejected from consideration. Synthesising the results from the drought indicators, several candidate events were selected (Table 4), and information was gathered on the impacts of the episodes in question, the majority of which was accessed from the British Hydrological Society Chronology of Hydrological Events (http://www.dundee.ac.uk/geography/cbhe/; see Black & Law, 2004). The major drought events of the early twentieth century can also be compared with drought catalogues published by Lloyd-Hughes *et al.*

(2009), which provide a regional assessment of hydrological and meteorological droughts in South East England (SEE) and South West England (SWE), to examine whether the featured droughts can be considered spatially extensive.

While there is a wealth of literature documenting the impacts of droughts from the early 1960s onwards, there are fewer sources available for earlier droughts. With the exception of the early 19th century droughts, there was some evidence of water supply and/or environmental impacts available for all these events, although the evidence for specific impacts within the study catchments is more limited. For the early 19th century droughts, the paucity of impact evidence may be due to the inevitable lack of information surrounding events which occurred 200 years ago. These droughts occurred at the end of the Little Ice Age, so may belong to a somewhat different climatic regime to that experienced in modern Britain. However, their severity, in terms of runoff deficiencies, suggest they would be ideally suited to testing contemporary water resource systems against very extreme events, well outside the normal range of behaviour considered in contemporary drought plans.

The drought selection for the workshops was undertaken based the critical periods identified using the reconstructed flow records and drought indicators and model runs for the period from 1865 (Wimbleball) and 1800 (Grafham) to date. The water resource modelling indicated that for Wimbleball reservoir the most severe droughts occurred during the period 1868-71, 1886-87 and 1895-96. Modelling showed that Wimbleball reservoir is relatively insensitive to multi-season drought because the pumped storage scheme has sufficient capacity to refill the reservoir every year. For Grafham reservoir multi-season droughts with dry winters are more important. The most severe water resources droughts occurred during the early 1800s and 1815-16.

There was time to consider two prolonged droughts in each workshop. Both used one entire drought (1868–71 for Wimbleball, 1815-17 for Grafham) and one very prolonged drought made by stacking two droughts together (1886-87 + 1895-96 for Wimbleball, 1807-08 + 1801-04 for Grafham). For the stacked droughts, preliminary modelling indicated that in both cases the reservoir would recover fully between the two events. The stacking therefore has the effect of contracting the wetter, easily managed period between droughts, allowing managers to explore their changing risk appetites as droughts continue for four or more years.

4. Water resources modelling

All water suppliers have numerical models of their water supply systems, used for understanding long-term system performance, system optimisation, and day-to-day operational decisions. The necessary complexity of these models makes them unsuitable for use in an interactive workshop: run times are often long, and it is rarely possible to interrogate the results until the end of the model simulation. This study developed simplified models that reproduce the fundamental aspects of system performance but allow decision makers to step through a drought with no prior knowledge of the drought in question or how it would evolve. The aim was to provide simple system state information – reservoir levels, rainfall, groundwater levels and three to six month forecasts of reservoir storage – to allow system managers to make decisions on drought measures month by month.

A simple reservoir behavioural model with was developed in an Excel spreadsheet. The model calculates reservoir storage on a monthly timestep:

$$R_t = R_{t-1} – D_t + I_t \qquad \text{(Eq. 1)}$$

Where:

R = reservoir storage (megalitres, Ml: 1 Ml = 1000 m^3)
D = demand (Ml)
I = inflow (Ml)
t denotes the current timestep, and t-1 the previous timestep.

Both of the reservoir systems in question are fed both from a natural catchment and, when necessary, by pumping from a larger river. Inflow, I, is calculated as:

$$I_t = C_t + P_t \qquad \text{(Eq. 2)}$$

Where:

C = catchment inflow (Ml)

P = pumped volume (Ml)

Pumped volume, P, is calculated from a series of conditions. No pumping is necessary if this month's demand is met by inflow or if the reservoir is above a defined level: this level varies monthly according to a predetermined "control rule". If the volume stored in the reservoir is below the monthly defined level, P is calculated according to abstraction licence conditions. In both cases these define a minimum flow that must be left in the river (often called the "minimum residual flow") and a maximum pumping volume.

Input data for this simple model is:

- river flow - a monthly time series for the duration of the simulation
- demand – a sequence of 12 monthly values representing current demand, repeated through the simulation
- reservoir capacity, initial volume and start date
- pumping conditions – maximum pumping rate and abstraction licence conditions.

In addition, the user interface allows a variety of interventions to be specified dynamically during the simulation. These interventions can be on demand or supply. Demand interventions reduce demand by a specified amount: for example, this could be the saving from extra leakage control or demand restrictions such as hosepipe restrictions. Supply interventions provide extra water either to put into the reservoir or to meet demand directly, reducing the demand on the reservoir. Combinations of supply and demand interventions allow the effect of all possible drought measures to be simulated.

Model outputs were validated against yields provided by the water companies by simulating reservoir behaviour over the period of record used to calculate yield (see, for example, Watts (2010) for a discussion of approaches to the calculation of yield). Good agreement was found, although small discrepancies were observed due to use of a monthly time step compared to the daily time step used in water companies' calculation of yield. In the Wimbleball model the use of a monthly time step produced a slightly smaller reservoir drawdown than observed in reality. To compensate for this target demands were set slightly higher than normal in the workshop to produce a more realistic drought response.

For reservoirs, drought measures are typically associated with drought trigger curves: these provide a guide for the reservoir manager on the introduction of different measures. These curves are incorporated in the model but do not trigger action automatically: thus the reservoir manager can decide when to take different actions, which can be introduced before or after the trigger curve is breached.

5 Drought workshop

Testing the complete water resource system requires an exercise that allows people to interact with a water supply system model and take decisions that alter the subsequent state of the system. Exercises are commonly used in emergency planning, often in a cycle that involves planning, training and then performing an exercise to test the plan and the response of the participants (Perry 2004). The aim of this study was to test the system rather than to train the individuals involved. Using experienced system managers meant that further training was not necessary.

The scenario exercises used in this project are based on a strategy game approach described by Toth (1994) and Toth & Hizsnyik (2008). Strategy games have been applied in many different situations including military strategies, corporate strategic planning and forecasting, public policy and disaster preparedness to bring together and assess knowledge from a number of fields identifying possible responses to complex management problems and how policy might need to be restructured. Although they are inevitably a simplification of reality they provide a way to integrate intangible and non-quantifiable factors into strategic planning. Strategy games are typically undertaken in workshop settings, allowing a facilitator to develop a view of the plausibility of the scenario from the participants' perspective, understand the difficulties and issues arising throughout the decision making process and to explore where both the different practitioners' understanding of the situation differs and where that of the practitioner differs from the researcher (Ringland, 1998).

Droughts are an unusual form of emergency, in that their start is not usually noticed and their onset and development is very slow (Wilhite et al 2005). A relatively simple version of a strategy game, which could be executed within a day, was therefore chosen. In this exercise the participants respond to emerging drought situation data, focusing on how this would affect decision making. Even this relatively simple approach requires detailed preparation so that the drought scenarios are plausible for the people playing the game. This approach also requires participants to be knowledgable about drought planning procedures and familiar with their role in drought management.

Participants for the workshops were drawn from the two water companies (operating the system), the Environment Agency (responsible for environmental management and much of the regulatory regime) and Defra, the Government department with overall responsiblity for drought management in England. To make the workshop manageable, only a few representatives of each organisation could be present. This meant that some aspects of drought management had to be assumed: for example, water companies were represented by people with overall responsibility for drought, but who would not necessarily have detailed knowledge of the operation of individual water treatment works. Some important stakeholders were excluded from the workshops and their responses had to be estimated by other participants: these included non-governmental organisations (NGOs) and individual water users.

Simple water resource reservoir spreadsheet models were developed for the case study areas based on information provided by the water companies (section 4). Additional hydrological information was also provided including rainfall, groundwater levels and river flows. Three to six month projections of possible future state based on repeats of twentieth century events were presented to aid decision-making. The data (on a graph and a spreadsheet) appeared on a screen that everyone in the room could see and the time step was operated manually so participants were able to ‘pause’ the model in order to explore and capture a decision point.

Decisions or reflections that emerged through the simulation 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 different levels of evaluation gave the participants an opportunity to reflect on the performance of the water companies, Defra and the Environment Agency at critical points throughout the droughts and to discuss lessons learned. The aim of the overview of the day was to draw out the main issues with regards to drought management. This included putting the scenarios in the context of existing management plans and determining whether these were sufficient or if there were some changes that could be made to make the management process more efficient and effective in the event of a long drought. This also provided an opportunity to discuss the strengths and weaknesses of the scenario game and how plausibly it represented the real world.

6 Outcomes and experiences

The main interventions required for each drought are shown in Table 5 (Wimbleball) and Table 6 (Grafham). In all of the droughts tested, a wide range of drought measures was necessary to maintain reservoir levels: in the most testing drought in each system, these measures were essential to avoid reservoir failure, defined as the reservoir emptying. In the early stages of drought, demand interventions were introduced. As the drought progressed, measures to take more water from the environment were used. As the drought continued, water companies turned to engineering options such as re-using abandoned sources and temporary water transfers between catchments.

For Wimbleball, the main feature of these droughts was the very rapid rate of drawdown of reservoir levels compared to recent experience. Drought triggers were passed very rapidly through spring and early summer, with the result that hosepipe bans were followed very quickly by further interventions to augment supply. In both droughts, significant extra abstraction was needed for two to three months, though expert opinion from regulators and the water company agreed that this water would be available. Demand was reduced by almost 20%, through a combination of water efficiency campaigns, garden watering restrictions, restrictions on commercial water use, and additional leakage control.

For Grafham, the first drought was no more severe than those experienced in the twentieth century, but continued for four years. The water company used hosepipe bans to restrict garden watering, but avoided restrictions on commercial water use. Extra abstraction from the Ouse at Offord (under a drought order) maintained reservoir levels. In the second drought, reservoir levels dropped more rapidly than experienced in the twentieth century. Restrictions on commercial water use were introduced, and in the later years of the drought, abandoned water sources were reintroduced, as well as a scheme to pump water upstream from the Fens to the Offord intake. This scheme was planned but not implemented in the 1976 drought, but is not included in the current drought plan. In this second drought, demand reductions were also almost 20%, reflecting similar views from both companies on the scope for managing demand during severe droughts. Total interventions at Grafham represented a smaller proportion of reservoir deployable output than at Wimbleball, but were in place for much longer, reflecting the much slower response of the Ouse catchment.

In many ways it is reassuring that both water companies could find options to make these supply systems operate through these extended droughts. This suggests that the system of water supply plans and drought plans provides an effective combination of measures that can cope with droughts longer than those of the twentieth century. It is probable that this conclusion could have been reached simply by simulation modelling, without the interactive workshop: it would be easy to programme a simulation model to introduce increasingly difficult interventions automatically as reservoir levels drop. The real strength of this study was in examining the different circumstances in which interventions would be made, hence exposing the thought processes of the different actors involved.

All participants agreed that the exercise proved valuable, making them question assumptions that were built into existing drought plans. It was particularly evident that droughts do not play out as neatly as the drought plan might suggest. Early in a drought, water companies tended to be reluctant to introduce demand measures such as restrictions on garden watering because they were concerned that the drought could recede and the restriction would damage customer relations. On the other hand, regulators saw these early, relatively painless demand measures as both a signal that the water company was taking drought seriously and an essential prerequisite either to further demand restrictions with a more serious economic and social impact or to supply measures that could damage the environment. During a real drought, such debates can be both acrimonious and divisive: in both exercises, the discussion allowed all participants to gain an improved understanding of alternative perspectives on the same problem.

Both water supply systems were tested with droughts more severe than those recently experienced. In both cases, water company managers introduced interventions that were not included in the drought plan, although the water companies had either used or examined the measures in detail during the 1976 drought. Discussions revealed that water companies are reluctant to include extreme measures in public drought plans, mainly because they are concerned that water customers might conclude that their water supply is not secure if such measures are necessary. Regulators, on the other hand, believe that a comprehensive drought plan should make water customers more confident that the company can maintain secure water supplies. Neither of these opinions appears to be backed by research. Even if such measures are left out of public plans, they should be recorded and investigated: any remaining staff with a memory of the 1976 drought will be approaching retirement in the next decade and this experience could be lost.

During the workshops there was much debate about the time it takes to implement legislative measures such as drought orders and permits (see Defra et al 2005 for details). Water companies tend to see the legislative steps as a barrier, while regulators see them as important checks on unnecessary supply restrictions and environmental damage. The discussions improved understanding from all perspectives and may lead to improved guidance for water companies.

Water companies tend to rely on trigger curves based on reservoir levels (figure 4) to prompt action. In some types of drought these static trigger curves may lead to unnecessarily delayed action: in one case, we found that a reservoir level dropped through the trigger curves so quickly that there was little time for interventions to take effect. Actions based only on reservoir level may fail to react properly to unusual circumstances such as very rapid reservoir drawdown: water companies could investigate multivariate triggers that include the rate of reservoir drawdown as well as the absolute level.

In England and Wales, drought has not caused water companies to introduce standpipes or rota cuts since 1976 (Doornkamp et al 1980). Most water companies have no experience of how water supply systems will perform in long droughts and appear to have given this problem little consideration (it should be noted that all water companies have emergency plans that allow them to respond to supply failures). In some systems, it may be possible to maintain a high proportion of normal supply for an extended period of drought operation. Such a system might be made of a number of different sources and draw from large rivers where flows recede slowly, perhaps because they are fed by groundwater. Other systems may have few reserves and might fail catastrophically (figure 5 is a conceptual model of these two conditions). The current water resources planning and drought planning systems would effectively treat both systems in the same way by looking at performance through recent droughts. Further work on modes of water supply system failure could reveal important insights into future water resources planning.

This could help to identify system development options that would increase resilience, which could in turn reduce vulnerability to climate change.

This work concentrated on the impact of drought on water supply, with the objective of maintaining supply through the drought. All of the interventions made would have social, economic and environmental consequences. The social and economic consequences would not be distributed evenly but would affect some people and sectors much more than others. The environmental impact of additional abstraction could damage important wildlife sites, possibly beyond recovery. This study did not attempt to quantify the scale of these impacts. Understanding these costs would allow water resources planners to decide whether it might be better to change system design standards to avoid such damage, or whether the current approach is an appropriate response to low probability, high impact droughts.

It is important to note that this approach to testing drought management was possible only because of the introduction of a statutory duty for water companies to prepare drought plans that are widely available. The open and collaborative system that this has engendered made these workshops possible and has allowed the identification of possible improvements to drought management.

7 Conclusions and recommendations

This paper describes an approach to testing drought plans that goes beyond the traditional engineering approach to engage both supply managers and regulators – the people responsible for making decisions during a real drought. The approach recognises that a water supply system includes not only the natural environment and the physical water supply infrastructure but also the institutions and people who manage the system, as well as the users of water. This wider framing of the problem has allowed the development of a broader understanding of the strengths of the drought planning framework as well as highlighting areas that would benefit from further work.

In any strategy game, however simple, a minimum level of plausibility is required to enable participants to engage with the problem. Participants of the workshop agreed that this had been achieved, with the scenario game replicating the experience of managing real water supply systems in a drought. However, time and resources limited the investigation to a very limited number of droughts in only two resource zones in England. In both cases it was not possible to model the full complexity of complete resource zones, but valuable insights into the operation of water supply systems during droughts were gained.

This work demonstrates that this participative workshop approach to testing drought plans is of great value to water companies in the UK and beyond, but that the resource implications are significant and should be understood before initiating a widespread programme. Aspects demanding significant attention are:

- The identification of suitable droughts and the development of appropriate hydrological data series to represent these droughts;
- The development of simplified system models that can be used interactively during the workshop;
- The need to involve representatives from water companies and their regulators.

It would be extremely beneficial to extend workshop attendance to representatives of customers and environmental groups. While water companies and regulators might find this difficult (many decisions are still seen as purely technical), wider involvement could provide important insights into the acceptability of different drought measures.

This work was conducted to test the drought plans and the resilience of the supply system, rather than to train participants. Even so, it is clear that the people involved gained additional understanding as a result of the exercise. It would be useful to develop similar processes for training inexperienced employees of water companies and regulators. Such exercises would not need to test the supply system to the same extent, but it would still be valuable to gather members from all groups together to make the exercise realistic.

One limitation of this work is that it looks only at surface water supply systems. There would be significant benefit in extending this approach to systems mainly or partially supplied from groundwater: droughts develop slowly in such areas but intervention can be difficult, with few opportunities to augment water supplies.

Given the complexities and cost of this approach, it will probably not be possible to apply it to every water supply system in England and Wales. Further work could help to prioritise systems, perhaps based on a simplified index of their vulnerability to drought. There is also a need for further technical work looking at alternative, more dynamic approaches to drought trigger curves and looking at how different water supply systems perform when they are close to failure. Further investigation of the social, economic and environmental impact of drought measures would inform a wider debate on the planned reliability of water supply systems.

Drought management is an important but often neglected part of maintaining adequate water supplies and protecting the natural environment. Effective drought plans are essential for good drought management: they avoid confusion and unnecessary delay during a drought, and provide an opportunity for water companies, regulators and water users to consider a range of possible drought responses. Drought plans often draw on the experience of a few expert practitioners. Inevitably, this biases plans towards responses that would have worked in the most recent drought. Systematic testing of plans by interactive simulation allows a wider group of participants to respond to a range of droughts. This paper demonstrates that the experience can be positive for all participants: exposing drought plans to scrutiny in this way should not frighten water suppliers but should be seen as an opportunity to improve plans and participation. Water suppliers should build on the results to refine or recast their plans, with the confidence that the resulting plan will provide an improved response to the next drought. The findings should also be used in the preparation of long-term water resources plans, helping to identify options that improve water supply system resilience. This will prove useful in preparing for climate change: a system that is resilient now should be able to cope better with future climatic conditions.

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Table 1 Characteristics of the two case study areas: Grafham and Wimbleball

Water supply system	Grafham	Wimbleball
Catchment	River Ouse at Denver Complex	River Exe at Thorverton
Baseflow index	0.74	0.51
Average precipitation (mm)	601	1295
Average losses (mm)	457	451
Average annual runoff (mm)	144	844
Flow gauge	Denver Complex	Thorverton
Gauge no	33035	45001
Reconstructed record period	1801-2002	1865-2002
Catchment area (km^2)	3430	601
Max. elevation (m)	167	519
Q95 (m^3s^{-1})	3.2	2
Q10 (m^3s^{-1})	31.7	39
Main reservoir	Grafham	Wimbleball
Abstraction points/inflows	Rivers Ouse and reservoir inflow	Natural inflow, River Exe, Exbridge pumped storage

Table 2 Maximum 36- and 60-month runoff deficiencies (and percentage of long-term average, LTA) for synthetic runoff series for the Ely Ouse (1801 – 2002) and the Exe (1865 – 2002)

36-month deficiencies				60-month deficiencies			
Rank	Runoff (mm)	% of LTA	End Date	Rank	Runoff (mm)	% of LTA	End Date
Ely Ouse							
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	550.62	70.28	Feb 1898
7	271.08	57.55	Jul 1865	7	571.83	72.99	Jun 1909
8	272.83	57.87	Feb 1896	8	572.05	73.03	Feb 1839
9	278.55	59.14	Aug 1974	9	572.99	73.06	Dec 1865
10	280.25	59.45	Feb 1946	10	591.36	75.48	Apr 1924
Exe							
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	3369.09	85.36	Jan 1897
5	1918.80	80.55	May 1944	5	3432.92	87.23	Sep 1902
6	1918.67	80.57	Jun 1950	6	3459.95	87.92	Nov 1965
7	1942.09	81.28	Jan 1974	7	3480.40	88.25	Mar 1993
8	1949.84	81.49	Dec 1871	8	3492.26	88.64	May 1872
9	1979.78	82.96	Feb 1903	9	3575.6	90.63	Mar 1946
10	2001.85	83.66	Dec 1898	10	3590.4	90.98	Sep 1936

Table 3 Ten longest drought deficits based on moving monthly Q70 flow threshold

Rank	Start	End	Duration (months)	Deficit Volume ($m^3 s^{-1}$)
Ely Ouse				
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
Exe				
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 **Description of candidate long drought events selected for consideration for workshops, with details of impacts and comparison with drought catalogues for South East England (SEE) and South West England (SWE) (Lloyd-Hughes *et al.* 2009)**

Event	Description	Comments & Impacts
Ely Ouse		
1801 - 1809	Highest DSI. Two notable 3-year periods of deficiency (1802 – 1804, 1806 – 1808). Former has 2^{nd} highest deficit volume	Very brief mention in BHS chronology of dried wells in somerset; no local evidence.
1813 - 1817	2^{nd} highest DSI. Sustained period of deficiency with highest deficit volume on record.	No known evidence of impacts.
1893 – 1896	3^{rd} highest DSI. 8th highest 3-year deficiency, with 5^{th} highest threshold deficit volume from Apr 1893 – Oct 1894.	Widespread impacts in Midlands and S. England. In Anglian, reports of dried wells, ponds, ditches and springs in 1893 and summer 1895
1901 – 1903	4^{th} highest DSI. 4th highest 3-year deficiency, with 3rd highest deficit volume (May 1901 – Feb 1903)	Significant rainfall deficits in SEE; groundwater and streamflow deficits exacerbated by earlier dry spell in 1890s. Large spatial variations, but impacts reported from west Midlands to southern England. In Anglian, reports of dry ponds and springs; reference to low ponds and failing wells in Great Ouse catchment.
1921 – 1923	5^{th} highest 3-year deficiency, with 8^{th} highest threshold deficit (Feb 1921 – Mar 1922)	Notable drought across most regions, especially the south; spatially coherent meteorological drought through 1921 in SEE drought catalogue. Dry rivers and recession of stream heads in southern England (Sussex, Surrey). Limited evidence of local impacts in BHS chronlogy
1933 – 1935	5^{th} highest DSI. 6^{th} highest 3-year deficiency, 4^{th} highest threshold deficit (Aug 1933 – Mar 1935)	Very coherent rainfall deficits in SEE through 1934. Serious water shortages reported in many eastern areas – particularly rural Essex. Low groundwater levels in south east England.
Exe		
1869 - 1872	8^{th} highest 3-year deficiency (up to Dec 1871) and 5^{th} highest threshold deficit (Apr 1870 – Sep 1870)	Reports of springs failing in Devon in 1869. Water shortages reported, e.g. Nov 1870 in Totnes, Devon. Reports of poor hay crops in the Exe catchment in summer 1870.
1887 - 1889	Highest 3-year rainfall deficiency, and 3^{rd} highest threshold deficit (Feb – Sep 1887)	Widespread impacts in the south west. Low river levels on the Kenwyn, water scarcity reported in Torquay. Poor water quality: the Exe at Exeter described as “little better than a sewer” (Symons, 1888)
1901 – 1907	Two notable 3-year deficiencies (1901 – 1903; 1904 – 1907) separated by wet interlude. 8^{th} highest threshold deficit in autumn/winter of 1904/1905)	Period of very dry winters in SWE, especially 1904/5. Numerous anecdotal reports of impacts of 1905 and 1906 drought in Exe catchment; failure of springs and village wells in Exe headwaters.
1919 – 1921	Not a protracted drought; not in top 10 deficiencies. But highest ranking threshold deficit from Feb	Period of three very dry winters, and protracted meteorological drought through 1921 in SWE. Anecdotal reports of long rainless periods in south

	– dec 1921, and high ranking deficit in 1919.	west England, but limited evidence of local impacts in BHS chronology
1931 - 1934	4th highest deficiency, and 2nd highest threshold deficit 1933 – Mar 1934)	Long period of coherent meteorological drought in SWE, spring 1933 – spring 1934. Limited evidence of local impacts, except for dry ditches in Somerset in Jan 1934.

Table 5 Wimbleball: measures implemented

	Scenario 1: 1868 to 1871 drought	Scenario 2: 1886 to 1890 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 more unusual	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 Beyond recent experience, particularly years 2 and 4 that required wide ranging drought management measures
Supply	o 129 Ml/d additional supplies needed for 2-3 months in third autumn o Used measures outside Drought Plan	o 139 Ml/d of additional supplies needed in Year 2 o 151 Ml/d of additional supply needed for 2 months in Year 4 o measures outside Drought Plan
Demand	o Hosepipe ban used o 15 percent reduction in demand	o Hosepipe ban and restrictions on Non Essential Use 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
Other issues	o Supplies seriously threatened in third year of drought o No public water supply failure o 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 measures outside Drought Plan	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 plan to maintain supplies

1110 **Table 6** **Grafham: measures implemented**

	Scenario 1: 1807/1808 + 1815/17	Scenario 2: 1801 to 1804
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 Long drought with high demand – most severe water resources drought for 200 years – causing rapid unprecedented drawdown of Grafham o Drought outside the range of normal company experience
Supply	o Operational improvements o Required balancing across zone o 90 Ml/d including hands off flow reduction	o Operational improvements o Required balancing across zone o Emergency plant – effluent re-use o Back pumping to Offord o 139 Ml/d including schemes that are not included in Drought Plan
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 Rutland used to balance supplies but this would also have been affected by this drought o Leakage control
Other issues	o Environmental impacts on Ouse Washes o Additional abstraction refused until all demand management measures in place.	o Speed of onset of drought problematic for water company

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