Environment Agency

Evidence

Understanding the performance of water supply systems during mild to extreme droughts

Report – SC120048/R

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Miranda Kavanagh

Director of Evidence

Executive summary

Objectives

Current water resources planning in England and Wales tests the resilience of public water supply systems against the worst historical droughts in the observed record (WRPG 2012). This approach, however, does not assess how a water supply system would respond when pushed beyond these historical design conditions.

This project aimed to understand the performance of different types of water supply systems to a range of droughts, including those that are more severe than the worst-case historical droughts, in order to identify the relative sensitivity of different systems when stressed beyond the drought conditions for which they are designed. The results of these 'stress tests' will help to improve our understanding of water supply system sensitivity to drought and identify whether systems respond differently when tested beyond the design conditions of current water supply planning approaches.

Methodology

Nine case study water supply systems were selected to represent the diversity of infrastructure configurations, catchment geology and climatological conditions found across England and Wales. The following steps were then carried out:

- develop simplified models for each case study water supply system
- develop a range of drought scenarios, hereafter referred to as the 'drought sensitivity framework', which includes events that are more severe than those experienced in the observed record
- apply the drought sensitivity framework to the case study models, in order to simulate system performance under drought conditions
- characterise the relative sensitivity of each system to the drought sensitivity framework in terms of system resilience and vulnerability

The drought sensitivity framework systematically explores a range of drought scenarios with varying rainfall deficit, duration and seasonality. This enables a rigorous and consistent comparison of drought impacts across water supply systems with different climatological characteristics. The sensitivity of the water supply system to drought was summarised using supply-demand performance metrics, which were presented as drought 'response surfaces'. The response surfaces from all the case studies were then analysed to identify similarities or differences in the systems' relative performance to the same range of drought scenarios.

Interpretation of results

The results show that the case study water supply systems typically fall into three groups: systems that experience either rapid failure, progressive failure or that exhibit low sensitivity or high resilience to drought. Rapid failure systems tend to be single season systems and are resilient against a large range of drought scenarios but typically reach a threshold of rainfall deficit where winter recovery becomes limited and the system begins to fail. Progressive failure systems tend to be multi-season systems and are sensitive to both drought duration and intensity, experiencing gradual decline in resource through successive years of longer droughts. Low sensitivity systems tend to be conjunctive use systems where supply deficits can occur but remain small for all but the most severe droughts considered. They are not affected significantly by ether drought duration or intensity.

The results suggest that conjunctive use systems that draw on diverse sources tend to be more resilient than systems based on a single source or group of sources with similar characteristics. The most resilient systems tested tended to be where reservoir or groundwater resources were supplemented by abstractions from large rivers with flows that are supported by natural catchment storage or artificial river regulation.

Although the case study results imply that key distinctions can be made in terms of supply system sensitivity, it was not possible to generalise the drought response based on the natural or infrastructural characteristics of the water supply systems. This is in part because of the small sample from which to draw conclusions (nine case studies) and partly because a system's response is the result of a complex interplay of many different system-specific characteristics, including climate, catchment characteristics, infrastructure characteristics, demand and licence constraints. In order to determine whether the development of a generalised typology would be possible, a much more comprehensive analysis across a multitude of system combinations would be required.

Potential applications

The drought sensitivity framework approach set out in this document has a wide range of potential applications in water resources planning, including the following:

- as an options appraisal tool to look at the relative benefits of drought management options, or to assess the impact of infrastructure changes or licence sustainability reductions on the system drought resilience
- as a screening tool to estimate a water supply system's response to droughts which have not previously been tested, either from the historical record as new evidence becomes available, or to assess the likely impacts of future climate change on system resilience.

Recommendations for further work

It is recommended that guidance is developed for water companies on how the sensitivity approach could be used to support the water resource and drought planning processes. Furthermore, in order to promote wider application and further refinement of the approach, it is recommended that research is also carried out to:

- incorporate spatial coherence into drought scenarios for application to larger water resource zones or for regional water resources planning
- test the drought sensitivity framework to assess the relative importance of temperature, and in turn evapotranspiration, when synthetically creating droughts
- compare the drought scenario framework approach with other synthetic drought methodologies to understand the benefits of different methods
- further explore drought resilience in conjunctive use systems (the finding that they are generally more resilient suggests that not only is there a deployable output benefit from conjunctive use but that there is an additional resilience benefit too, and the reasons behind this should be explored)
- assess the degree to which system operating rules influence drought resilience
- further investigate the drought sensitivity groundwater supply systems, including infrastructure constraints such as borehole depth
- consider application of the method to other sectors (for example agriculture or hydropower) and to factors other than drought

Acknowledgements

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- Environment Agency: Stuart Allen, Stuart Sampson, Glenn Watts
- Defra: Adrian Brookes
- Dŵr Cymru/Welsh Water: Ian Brown
- Southern Water: Meyrick Gough
- South West Water/UKWIR: Paul Merchant
- Thames Water: Steve Tuck
- Yorkshire Water: Miranda Foster

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1 Introduction

1.1 Background

The current approach to water resources planning in England and Wales assesses the resilience of public water supply systems against the worst historical drought in the observed record (WRPG 2012). The principal limitation of this approach is that the planning process is constrained by the presence or absence of specific historical drought events. This leads to design standards for water supply systems that may be resilient to all that has come before the planning process but that could be vulnerable to events more severe than those in the historical record. Furthermore, the current approach can also lead to regional inconsistencies in the design standard for water supply systems, as the worst historical drought varies in its magnitude and characteristics across the country.

Previous research has looked at the impact of long duration droughts on water resources by testing the resilience of the drought planning process through scenario testing of two water company supply systems (von Christierson et al. 2011, Watts et al. 2012). The project found that the two systems (including the physical water supply system, drought actions, and the people who make decisions) performed well through some very severe droughts. However, during the later years of extended droughts, large engineering projects were required to guarantee continuity of supply. It was not clear how typical these two systems were and questions remained over the speed and manner in which different systems may breach their design standards when taken outside the 'design drought' experience, whether that be in terms of the duration of drought, severity or a combination of both.

1.2 Objectives

With these issues in mind, the overall aim of the project was to identify the relative sensitivity of different types of water supply systems to a range of possible droughts, including those that are more severe than the worst-case historical droughts for which they have previously been tested. The intention was to use this greater understanding of sensitivity to explore the characteristics that make for drought resilient systems (for example geographic location, infrastructure). With such knowledge we can begin to consider ways in which we can reduce sensitivity and increase the resilience of systems.

Specific objectives were as follows:

- to assess the impact of a range of drought scenarios on a variety of water supply systems
- to present the comparative sensitivity of systems to drought and identify reasons for failure
- based on these assessments, to investigate whether it would be possible to identify a generalised typology of supply system sensitivity to drought that could be applied to all systems to draw inference on risk to supply from drought

1.3 Approach

An assessment of the results from a number of case studies was carried out in order to develop our understanding of system performance under drought conditions. This approach comprised the following steps:

- Develop simple models for a range of water supply systems. Case study supply systems have been selected to represent the diversity of infrastructure configurations, catchment geology and climatological conditions found across England and Wales.
- Develop a range of drought scenarios, which includes events that are more severe than those experienced in the observed record. This systematic approach to drought scenarios defined them against average conditions, thereby avoiding the problem of assigning return periods to events more severe than historically observed.
- Apply the scenarios to the case study models, in order to simulate system performance under drought conditions.
- Use a variety of analytical techniques to assess the scenario modelling results.

The analysis of model results has been used to characterise system sensitivity to drought in order to address two main research questions:

- Under what drought circumstances do systems begin to fail (that is enter a supply-demand deficit)?
- Once initial failure has occurred, how do systems respond to longer and/or more severe drought scenarios?

The extent to which these results could be used to develop a generalised typology of supply system sensitivity to drought was then investigated.

1.4 Structure of this report

The remainder of this report is structured in the following manner:

- The development of the case study models is described in section 2, including selection of case study systems, development of hydrological and system models, development of drought scenarios and post-processing and presentation of scenario results.
- Case study model results are provided in section 3.
- A comparative analysis of the sensitivity to drought of the case study supply systems is presented and discussed in section 4.
- The conclusions of the study and recommendations for further work are set out in section 5.

2 Case study development

2.1 Introduction

This section sets out how the case study models and associated drought scenarios that form the basis of the project were developed. The overall methodology is briefly described, followed by commentary on the selection of case studies. Further detail is then presented on the development of the case study models, and on the development of drought scenarios. Finally, an overview of the methods used for post-processing and presentation of modelled scenario results is provided.

2.2 Methodology

The overall methodology applied involves the application of water supply system models within a consistent drought scenario framework, in order to simulate system performance in a manner that allows it to be compared across systems with diverse characteristics.

The system models developed are based on actual supply systems, as described further below. They integrate a representation of the hydrology and hydrogeology of sources with the configuration of the supply systems, including storage elements, infrastructural and licence constraints. The models are intended to reproduce the key characteristics of system behaviour, but are not as detailed as those typically used by water companies as part of their water resources planning activities. As such, while they will not exactly reproduce the results of water company planning models, it is expected that the main characteristics of the case study systems' performance will be similar. Model results have been discussed with the relevant water company in order to ensure that the water company is content that the simple models used in this study provide an adequate representation of system performance.

The water supply systems have been tested against a range of drought scenarios using the scenario-neutral approach originally developed by the Centre for Ecology and Hydrology (CEH) for the Defra and Environment Agency funded project 'Regionalised impact of climate change on flood flows' (Prudhomme et al. 2010, 2013). This provides a framework in which the impact of a range of scenarios is systematically calculated to quantify the sensitivity of a system to a climate risk (in this case droughts) in the form of response surfaces. All of the case study models are applied within the same consistent framework, which is hereafter referred to as the 'drought sensitivity framework'.

2.3 Case study selection

Nine case study water supply systems have been assessed in this study. These systems are either water resource zones (WRZs) in their own right, or, in some cases, a distinct part of a larger integrated water resource zone. Case studies have been selected to represent the diversity of water supply system types found across England and Wales, in terms of size, climatology, geology, mix of surface and groundwater sources, infrastructure and mode of operation. The location of the case study systems is shown on Figure 2.1 and their characteristics are summarised in Table 2.1.

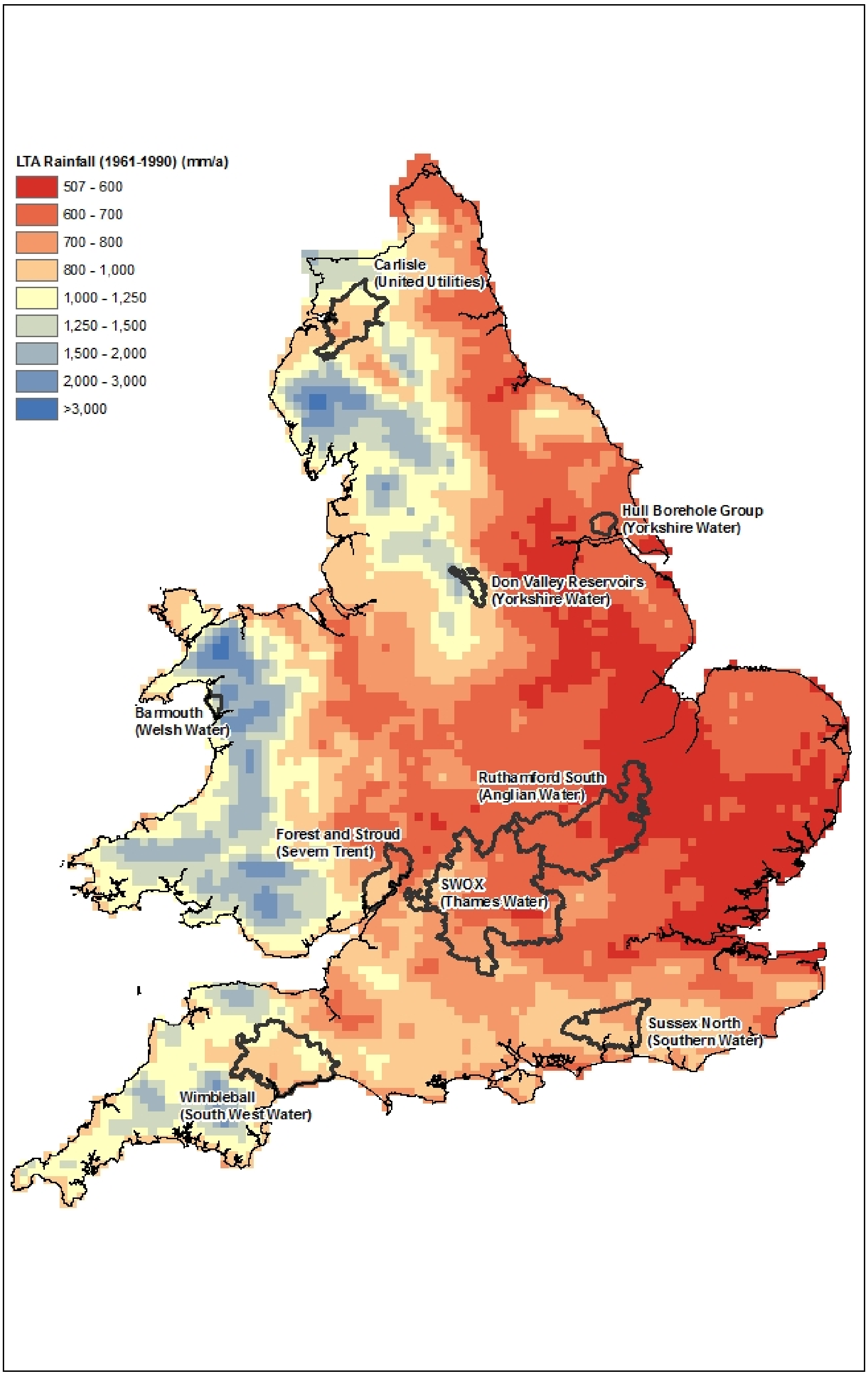

Figure 2.1 Location of case study water supply systems

Table 2.1 Summary of case study water supply systems

Case study name	Water company	Annual average rainfall, 1961–90 (mm/a)	Deploy-able output (Ml/d)	Description
Barmouth WRZ	Dŵr Cymru/Welsh Water	1,293	2.1	Single, upland gravity-fed surface water reservoir (Llyn Bodlyn), upland catchment in mid-Wales
Carlisle WRZ	United Utilities	959	34.7	Direct abstraction from the River Eden and abstraction from the River Gelt to Castle Carrock Reservoir, Cumbria
Don Valley Reservoirs	Yorkshire Water	1271	80.4	Upland gravity-fed reservoir cascade, South Pennines
Forest and Stroud WRZ	Severn Trent Water	801	45.0	Direct abstraction from the River Wye combined with limestone and sandstone groundwater sources (springs and boreholes), Gloucestershire
Hull Borehole Group	Yorkshire Water	682	51.0	Chalk well and adit groundwater sources, East Yorkshire
Ruthamford South WRZ	Anglian Water	605	276.9	Direct abstraction from River Great Ouse, pumped storage reservoir at Grafham Water, greensand groundwater sources, Bedfordshire
Sussex North WRZ	Southern Water	844	71.3	Direct abstraction from Rivers Rother and Arun, reservoir storage, groundwater abstraction from Hardham Basin (greensand), Sussex
Swindon and Oxford (SWOX) WRZ	Thames Water	696	326.6	Abstraction from the River Thames to pumped storage reservoir at Farmoor combined with abstraction from chalk and limestone groundwater sources, Wiltshire/Oxfordshire
Wimbleball WRZ	South West Water	940	103.6	Abstraction from the River Exe, pumped storage to Wimbleball Reservoir, and with groundwater abstraction from sandstone sources, Devon

2.4 Model development

2.4.1 Hydrological models

Catchment hydrological models have been created and calibrated for surface water sources using HR Wallingford's water resources modelling framework, which uses a modified form of the PDM-model (Moore 2007). Each hydrological model requires inputs of MORECS potential evapotranspiration (PET, Thompson et al. 1982) and GEAR precipitation (Tanguy et al. 2014, Keller et al. 2015) and a historical flow series for calibration. Model parameters are automatically generated using Latin hypercube sampling in order to explore multiple model realisations during the calibration. The models are calibrated towards lower flows for appropriate application in a water resource context using a Log Nash–Sutcliffe goodness-of-fit criterion, volume error and visual inspection of the flow hydrograph and flow duration curves. Across the nine case studies, a total of 16 new hydrological models were developed and calibrated. These include models of the Rivers Exe, Thames, Wye, Rother, Bedford Ouse and a number of reservoir catchments in Yorkshire, Devon, Cumbria, North Wales and Hampshire.

2.4.2 Hydrogeological models

A spreadsheet-based lumped recharge and aquifer storage model developed by Amec Foster Wheeler has been used in this project. Recharge is calculated using a daily soil moisture accounting approach based on that developed in FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998). A simplified aquifer response function (ARF) groundwater model is then used simulate groundwater storage, including the effects of abstraction (Erskine and Papaioannou 1997).

The model requires input of catchment soil and vegetation distributions and associated parameters to drive the daily soil moisture balance, as well as the aquifer parameters (transmissivity, storage coefficient and an aquifer 'length' parameter) to drive the output of the groundwater model. Models were calibrated by visual inspection of model results against observed groundwater level and spring flow series.

Three sets of groundwater models were developed as part of this study, representing the Hull Borehole Group (chalk), the Hardham Basin in the Sussex North WRZ (greensands), and limestone spring sources in Forest and Stroud WRZ. Groundwater sources were not considered sensitive to drought for other case studies with a groundwater component to their supply, including Ruthamford South, SWOX and Wimbleball water resource zones. As a consequence, groundwater modelling was not considered necessary for these systems.

2.4.3 Water resource systems models

The requirement of the water resource systems modelling is to replicate the key components of each case study water supply system, to a sufficient degree of complexity, in order to capture the key system components and their response to drought. To achieve this, HR Wallingford's water resources model has been used, which is based on a mass-balance, node and link structure similar to conventional models used widely in the water industry (for example Aquator/Miser) but without including the same degree of detail when representing the supply system and its infrastructure.

Each case study includes its main surface water and groundwater sources with demand centres typically aggregated into as coarse a spatial unit as possible while ensuring the correct combinations of demands can be applied to the system sources.

The systems models have been developed using information provided by the water companies on system demand profiles, abstraction licence constraints and system control rules.

Model schematics of the water resources systems models and a description of each case study supply system can be found in Appendix A.

2.4.4 Standardisation of system performance

In developing new simplified case study models across various water companies a number of differences exist between these new models and the existing water company developed models. These differences are a result of using different hydrological/hydrogeological models with different input climate data and the simplified representations of each water supply system. Furthermore, the demand values provided by water companies for developing each case study represent the demand that could be taken from their respective systems model assuming a given level of service which differs between each water company. The result of these factors is that each case study system model is potentially operating to a different level of risk, which means that the point of system failure to drought is not readily comparable between the case studies.

In order to standardise the level of risk between each case study the maximum demand which can be taken from each system model without the system failing was calculated for the period 1961–2012. For each case study this represents the maximum resource that could have been supplied in the worst recorded drought during this period.

In systems with just a single demand node this was achieved using a binary search algorithm. Where a system has multiple demand nodes a multi-objective genetic algorithm (Deb et al. 2002) was used in order to capture any interactions between competing demands abstracting from the same sources. Further details on the standardisation of system performance can be found in Appendix B.

2.5 Drought sensitivity framework

2.5.1 Drought parameters

A drought sensitivity framework was implemented to test the resulting interaction of intensity and duration of droughts on water supply systems. This was defined as a matrix of rainfall deficit duration and intensity (expressed as percentage of long-term average, LTA), with duration ranging from 6 months to 5 years by 6-month increments and mean intensity ranging from -10% to -80% of LTA. In addition, drought seasonality was tested by imposing two drought starts: April and October; and two drought profiles: uniform or seasonal, with deficits concentrated in winter or summer, yielding a total of four different drought profiles:

- October start with uniform rainfall deficit (‘ProfOctober’)
- April start with uniform rainfall deficit (‘ProfApril’)
- October start with rainfall deficit concentrated in winter (‘ProfWinter’)
- April start with rainfall deficit concentrated in summer (‘ProfSummer’)

2.5.2 Derivation of drought sequences for model input

Each individual drought scenario is of 30 years duration, and comprises three distinct periods: a 10-year run-in period, to ensure that each drought starts from identical initial conditions; a drought period of varying duration defined according to the drought parameters presented above; and a recovery period of at least 15 years (depending on drought duration). Each period is characterised by monthly intensity in rainfall and PET, expressed as a percentage of LTA.

For both run-in and recovery periods, rainfall and PET intensity is equal to 100% LTA (average conditions) for all months.

For drought periods, rainfall and PET intensity are defined independently. PET intensity is the same across the drought duration of all profiles, equal to 100% of LTA (average conditions) for uniform and winter droughts and to 120% of LTA (increase of 20% in PET) for summer droughts. Rainfall deficit is the same across the drought duration for the uniform profiles. For winter and summer profiles, rainfall deficit varies through the drought duration following a cosine curve with a maximum deficit in January (winter profile) and July (summer profile). Details of the definition of monthly rainfall deficits for the variable profiles are provided in Appendix C.

For each drought scenario, synthetic rainfall and PET sequences are created by resampling months with intensity closest to the intensity profile from local daily historical rainfall and PET (for example January 1983 rainfall corresponds to 101% of LTA for January and will therefore be selected to represent January in the run-in and recovery profiles). Note that consecutive time steps can be sampled from different years and that rainfall and PET are resampled independently.

2.6 Post-processing and presentation of scenario results

2.6.1 System performance metrics

The response of each case study system was analysed to identify under which drought scenarios the system enters a supply-demand deficit. In order to derive a common set of criteria that can be applied to all case studies irrespective of their characteristics, metrics have been calculated based on the system demands as summarised in Table 2.2. In order to simplify the analysis only a single metric is presented in section 3. This metric is the proportion of unfulfilled demand which represents the total additional resource that would be required in order to mitigate any supply-demand deficits over the duration of the drought event. Results for the other metrics defined in Table 2.2 are presented in Appendix D.

Table 2.2 Summary of water supply system performance metrics

Performance metric	Description
Total unfulfilled demand (Ml)	The total unfulfilled demand in millions of litres during the drought
Proportion unfulfilled demand (%)	The total unfulfilled demand as a proportion of the total requested demand during the drought
Proportion unfulfilled demand per day (%)	The daily average unfulfilled demand as a proportion of the requested demand on days with a supply-demand deficit
Deficit days (days)	The total number of days that experienced a supply-demand deficit
Proportion of deficit days (%)	The proportion of days with a supply-demand deficit during the drought event

2.6.2 Drought response surfaces

The results from the case study drought scenario modelling provide three dimensions of information: drought duration, drought intensity and system performance. In order to visualise the results, drought 'response surfaces' have been created to summarise the system response to the range of drought scenarios. The response surfaces display the drought characteristics of duration on the x-axis and intensity (rainfall deficit with respect to LTA rainfall) on the y-axis with the chosen system performance metric represented using coloured squares. Each square within the response surface therefore represents the system response to a particular combination of drought duration and intensity. The grey regions of the response surface represent scenarios where there is not a supply-demand failure and white areas represent scenarios with the smallest supply-demand failure.

In order to provide some context to the drought scenarios, historical rainfall data for the period 1961–2012 have been analysed to calculate the same drought characteristics as those that have been derived in section 2.5 and have been plotted on to the response surfaces using black stars.

Drought response surfaces have been created for each of the four drought scenario profiles defined in section 2.5.1.

3 Case study results

3.1 Introduction

The results from the case study water systems modelling are presented in this section of the report. Section 3.2 presents a comparison of the differences between the case study systems using a single consistent drought profile across all systems. The effects of variations in timing of drought initiation and seasonal variation in rainfall deficits are then described in section 3.3 by using all four drought profiles across three selected case studies.

3.2 Comparison of case study results

This section includes the results for drought response surfaces from all nine case studies for drought scenarios starting in October with a flat profile of rainfall deficits, which can be seen in Figure 3.1. This ‘flat’ profile with no seasonality was chosen because it simplifies comparison of case study systems compared to the use of the seasonally varying profiles.

The variation in colours across the response surfaces highlights the case studies which have the highest unfulfilled demand (for example Don Valley) and the lowest unfulfilled demand (for example Forest and Stroud). The response surfaces can be broadly grouped as higher impact (Barmouth, Don Valley, Hull, Ruthamford South, and SWOX), medium impact (Carlisle and Sussex North) and lower impact (Forest and Stroud and Wimbleball).

For case studies such as Wimbleball and Forest and Stroud the response surfaces demonstrate that a large number of the drought scenarios can cause a deficit in the supply-demand balance but that the overall impact of this deficit is very small, as indicated by the large white areas.

The ranges of the grey squares demonstrate the range of drought scenarios under which the case study supply systems are able to maintain supply. Across the majority of the case studies the systems can be seen to be resilient to larger rainfall deficit events at short durations but the resilience to the same percentage precipitation deficits decreases as the duration of the drought increases.

The historical drought events from the observed record provide historical context to the drought scenarios are plotted as stars on the response surfaces. The ‘envelope’ of historical events typically lies close to the start of the system failure, which is to be expected as the system demand has been standardised so it is just fulfilled during the worst historical drought on record. As a consequence the systems should in general begin to enter a supply-demand deficit when a drought becomes more severe than those which have been previously experienced.

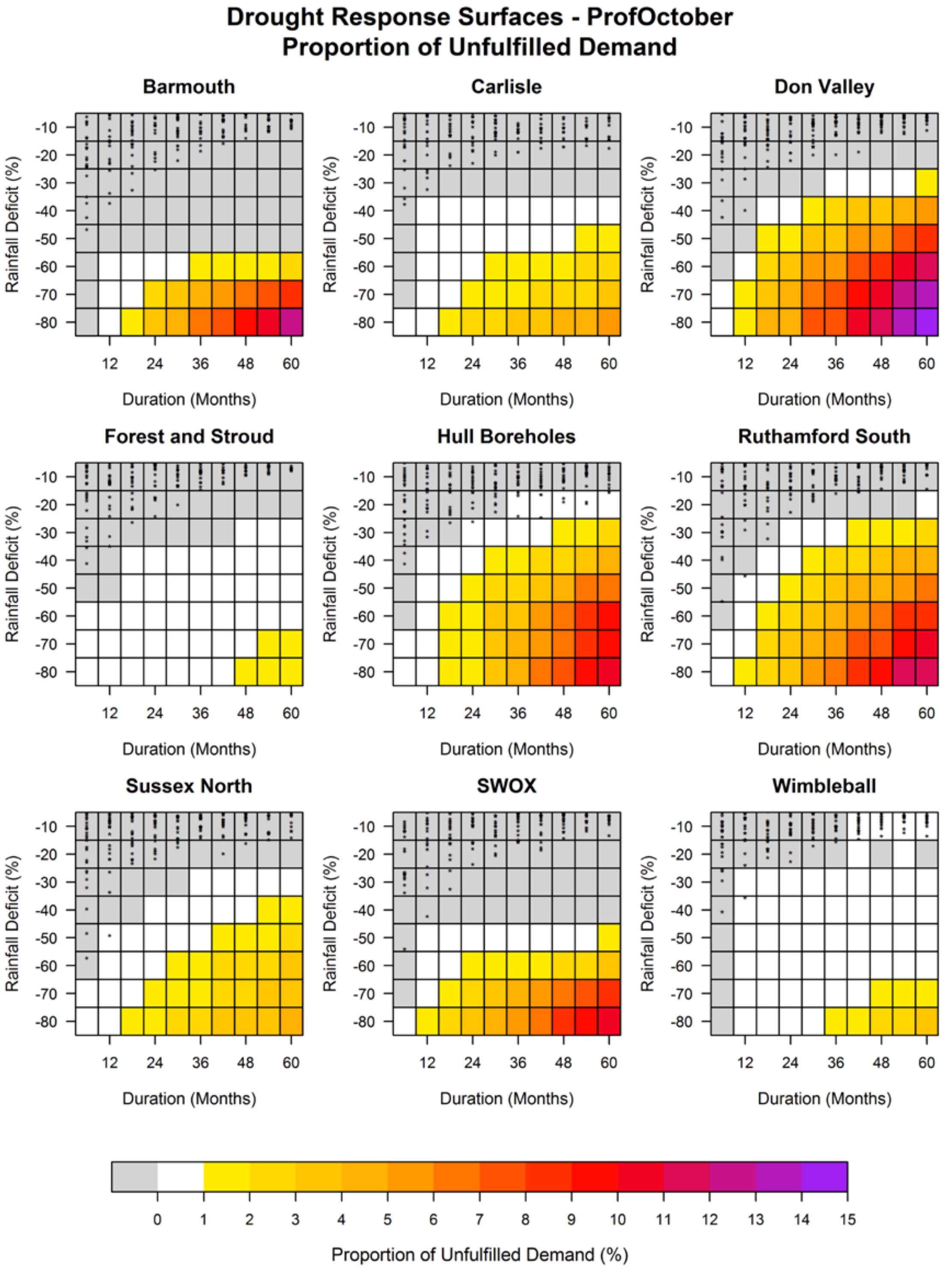

Figure 3.1 Drought response surfaces for all case studies using the ProfOctober profile for the proportion of unfulfilled demand metric

3.3 The effects of seasonal variations

All of the four drought profiles described in section 2.5 were processed through the case study water supply models. The resulting response surfaces are shown for Sussex North, Barmouth and Don Valley in Figure 3.2, Figure 3.3 and Figure 3.4 respectively to evaluate the effects of variations in the timing of drought initiation and seasonal variation in drought intensity. These three case study systems were chosen because they represent the range of responses observed across all nine systems and allow us to explore seasonal variability in a manageable way.

For Sussex North the start date for the drought, either April (ProfApril) or October (ProfOctober), dictates how quickly from the drought inception the water supply system enters a supply-demand deficit. Where a drought begins in October, and therefore the winter refill/recharge is reduced, supply-demand deficits can typically occur in the summer immediately following the drought inception. In contrast, a drought scenario beginning in April only realises a supply-demand deficit if it continues through the following winter and into the next summer. In the longer duration drought scenarios, the importance of the start date diminishes significantly.

For Barmouth the drought start date has less impact on the timing of the resulting supply-demand deficits occurring. This is due to the relatively high precipitation remaining with even a large proportional winter precipitation reduction being able to refill the comparatively small Llyn Bodlyn. The supply system is therefore able to maintain supply for a single season followed by a winter recovery for all but the worst drought scenarios.

For Don Valley the drought scenarios that start in October, and therefore initially reduce the winter refill, can lead to supply-demand deficits the following summer (for example 6 month droughts) for the largest precipitation deficits, whereas the equivalent 6-month duration drought starting in April maintains a supply-demand surplus through the summer.

The seasonally variable drought profiles cause an enhanced precipitation deficit in either winter (ProfWinter) or summer (ProfSummer). In addition, the 'ProfSummer' profile also has higher PET rates. The impact of seasonal variation on the water supply system response is typically to cause supply-demand deficits to occur 6 months earlier and/or as a consequence of smaller rainfall deficits when compared to using just a flat profile for shorter duration drought scenarios. In general terms it highlights the season to which the supply system is most sensitive (for example winter refill/recharge or enhanced summer drawdown). For instance Barmouth is more vulnerable to a larger number of the summer drought scenarios (more coloured squares) but the winter drought scenarios have a higher impact (higher unfulfilled demand). In contrast, Don Valley is more vulnerable to the winter drought scenarios but also experiences a higher impact from them too.

Although some differences due to the timing of drought initiation and seasonal variability are apparent, the four profile types produce broadly similar results for a given case study and the differences between the different case studies presented in section 3.2 are more notable than the differences between the seasonal drought profiles for any given case study. In order to simplify further analysis and comparison between case studies, only the ProfOctober drought scenarios, which represent a flat long-term average deficit beginning in October, will be presented and discussed in the remainder of the report.

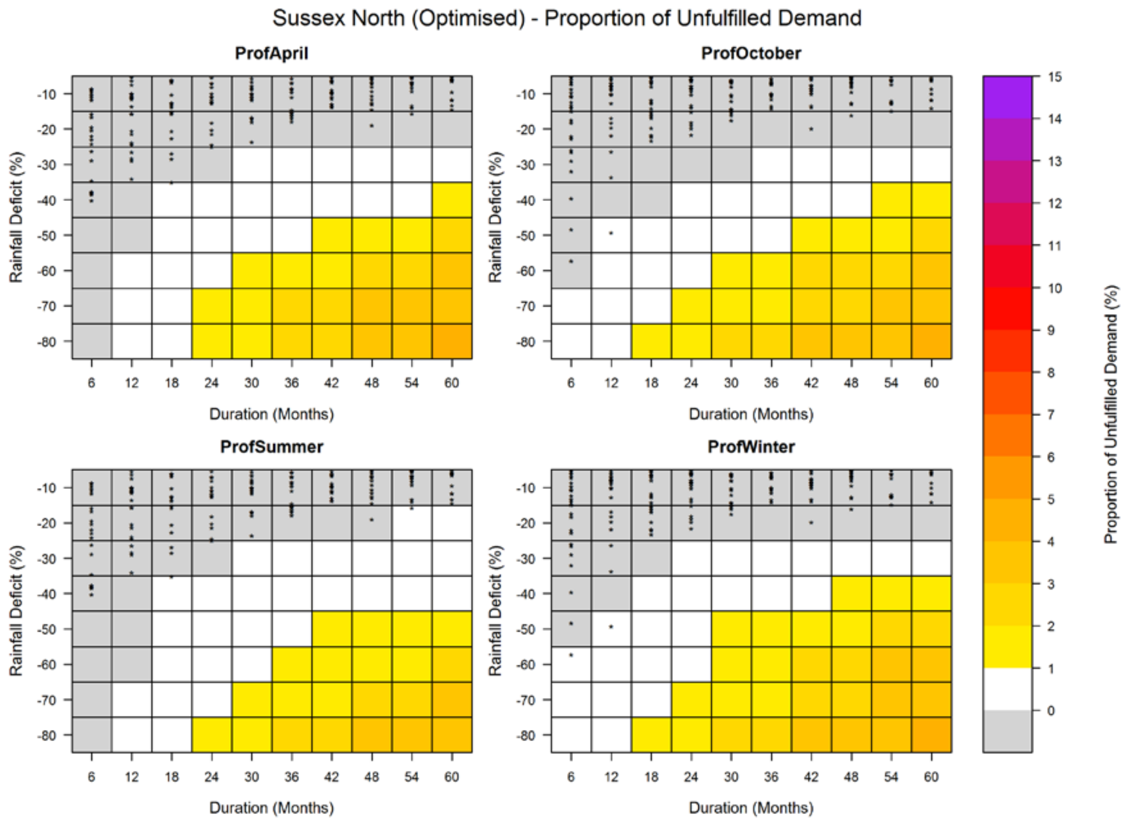

Figure 3.2 Drought response surface for Sussex North for the proportion of unfulfilled demand metric

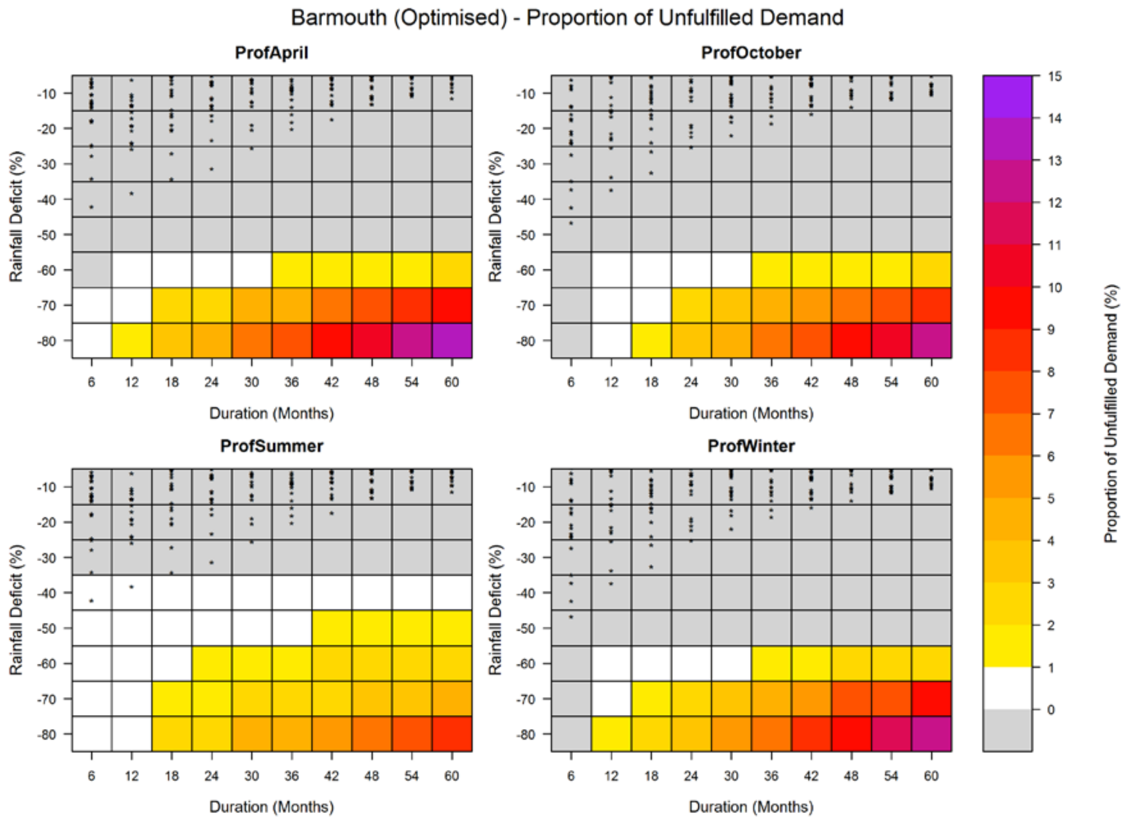

Figure 3.3 Drought response surface for Barmouth for the proportion of unfulfilled demand metric

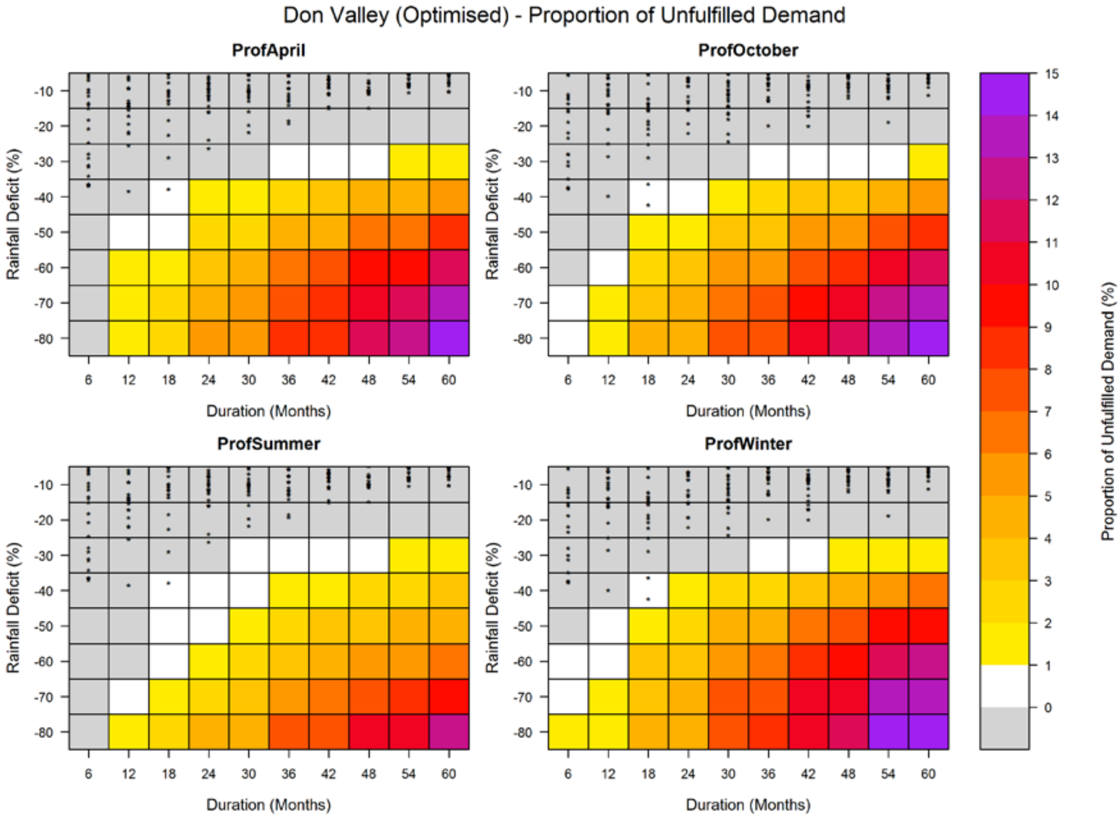

Figure 3.4 Drought response surface for Don Valley for the proportion of unfulfilled demand metric

4 Evaluation of drought sensitivity

4.1 Introduction

Following on from the presentation of the case study results in the form of response surfaces in section 3, further assessment of these response surfaces is presented in this section, with the objective of gaining further insight into the response of the case study systems to extreme drought. This further assessment seeks to explore two principal questions:

- Under what circumstances do systems enter a supply-demand deficit?
- Once initial failure has occurred, how do systems respond to longer and/or more severe drought scenarios?

In order to address these questions, a number of further assessments of the response surface data presented in section 3 were carried out, as described in the following sub-sections.

In reading the following section, it is important to bear in mind that all scenarios tested (that is combinations of rainfall deficit and duration) are independent. It should also be noted that the analysis presented in this section is based only on results from the ProfOctober drought scenarios (October start with uniform rainfall deficit).

In the following discussion, the term ‘failure’ is used to describe the condition in which a supply-demand deficit occurs.

4.2 Under what circumstances do systems enter a supply-demand deficit?

This question was explored through extracting information from the response surfaces regarding the combinations of drought intensity and duration under which supply-demand deficits begin to occur (that is, the circumstances under which system failure is initiated).

Figure 4.1 shows curves for each case study representing the maximum rainfall deficit under which system demand can be satisfied across all drought durations. With regard to the response surfaces presented in Figure 3.1, these curves represent the location of the boundary between grey-shaded squares and white squares, and are referred to as the system ‘failure boundary’ in the following discussion.

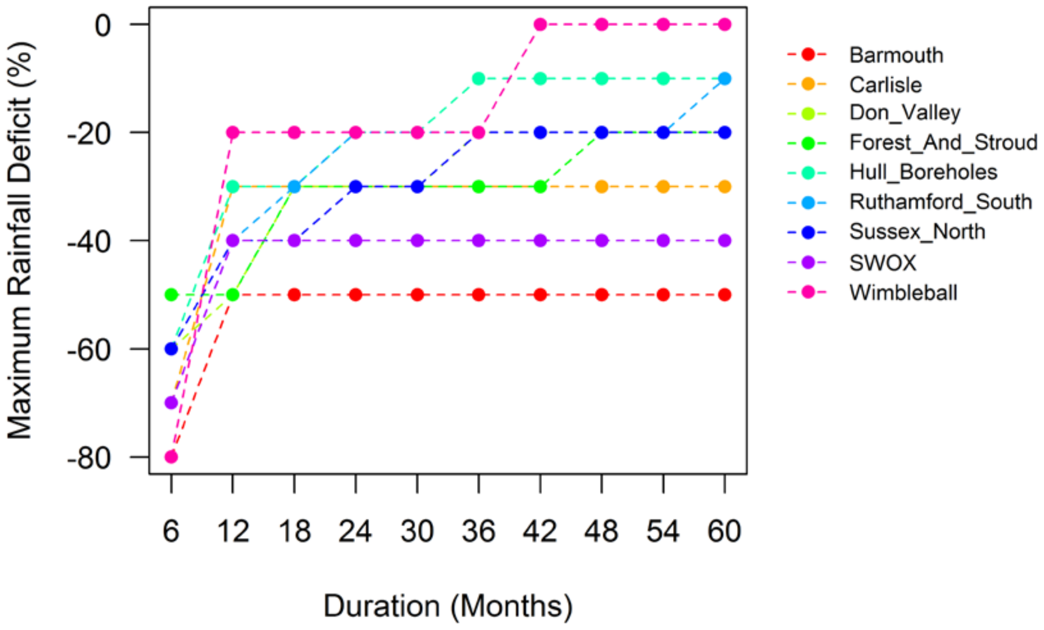

Figure 4.1 Maximum rainfall deficit under which full system demand can be satisfied

This figure suggests that all the systems considered are resilient to short droughts (that is those of less than 12 months duration). All the systems can withstand a 6-month drought with a rainfall deficit of up to 50%, with some systems, such as Barmouth and Wimbleball, able to withstand the maximum 80% rainfall deficit tested within the drought sensitivity framework.

Considering longer droughts, two distinct types of behaviour can be discerned in terms of shape of the failure boundary:

- A 'flat' failure boundary, in which a constant maximum rainfall deficit under which demand can be satisfied, occurs for drought durations of longer than 12 or 18 months. Barmouth, SWOX, and Carlisle exhibit this behaviour.
- A 'stepped' failure boundary in which the maximum rainfall deficit for which demand can be satisfied progressively decreases with increased drought duration. All of the other case studies fall into this category, with the exception of Wimbleball, which is discussed further below.

The implication of this is that systems exhibiting a flat failure boundary are most vulnerable to short droughts and relatively resilient to longer droughts; given drought intensity tends to reduce with increasing duration for events of equal likelihood. In contrast, systems exhibiting a stepped failure boundary may be vulnerable to a range of drought durations of similar likelihood, including longer duration, lower intensity events.

The Wimbleball system is less easy to categorise into either of the two failure response types outlined above. Supply-demand deficits are typically very small, but occur quite readily, particularly for longer droughts. This is largely related to assumptions made about groundwater availability for longer droughts, coupled with natural variability in river flows. These competing factors mean that the location of the failure boundary within the response surface is poorly defined in comparison to the other case studies.

In considering system resilience, it is also instructive to consider how far the failure boundaries for each of the case studies sit outside the range of historically recorded droughts. This is summarised graphically for all case studies in Figure 4.2, in which the 'rainfall deficit buffer' for each system is presented against drought duration. The rainfall deficit buffer is the difference between the maximum rainfall deficit observed in the historical record (1961–2012) and the maximum rainfall deficit under which system demand can be fully satisfied. In terms of the response surfaces presented in Figure 3.1, it represents the difference between the envelope of historical events plotted with asterisks and the system failure boundary.

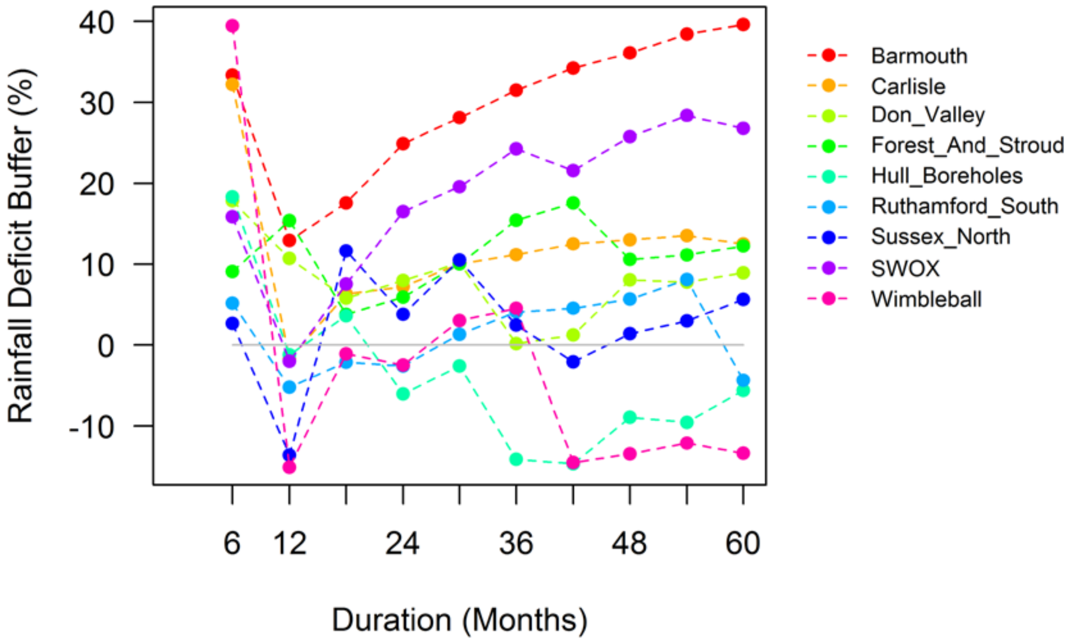

Figure 4.2 Difference between rainfall deficits for maximum observed historical drought and those under which system demand just remains fully satisfied ('rainfall deficit buffer')

The standardisation procedure described in section 2.4.4, which was used to ensure that demand was just met for all systems under the worst-case historical drought, has resulted in the worst historic drought converging with the maximum rainfall deficit possible before failure for certain drought durations. Figure 4.2 suggests this occurs most commonly for the 12-month event, which is indicative of the duration of the worst-case historical drought that was used for standardisation of system demands.

It is also notable that several of the rainfall deficit buffer curves drop below zero, indicating that supply-demand deficits would occur under conditions observed in the historical record. This would not necessarily be expected, since the system models have been optimised to ensure that demand can just be satisfied for the worst-case historical drought. However, it should be borne in mind that once optimised, the models have been tested within a synthetic drought sensitivity framework, rather than against drought sequences drawn from the historical record. In particular, variations in the sequencing of rainfall inputs during the synthetic drought compared to historical droughts of the same duration and average intensity could lead to slightly different outcomes. Therefore, some marginal supply-demand deficits might occur for some combinations of average drought intensity and duration that would not occur if tested against events of the same overall characteristics from the historical record.

Consideration of the shape of the curves presented in Figure 4.2 suggests that, once again, two main behaviours emerge from the case studies considered:

- An 'elongated v' or 'tick' shape, in which the rainfall deficit buffer reaches minimum values for droughts of 12 or 18 months duration, but then progressively increases for longer durations. Those systems exhibiting this profile most clearly are the same as those which exhibited a flat failure boundary, namely Barmouth, SWOX and Carlisle. However, Ruthamford South also demonstrates a rainfall deficit buffer profile resembling this shape, although it is less pronounced than for the other three case studies in the class.
- An 'oscillating' shape, in which the rainfall deficit buffer varies within ±20% of zero, and there is no trend with increasing drought duration. Hull, Wimbleball, Forest and Stroud, Sussex North and Don Valley fall into this category.

For those systems with a 'tick' shape, rainfall deficit buffer minima are clearly reached for drought durations corresponding to those of the worst-case droughts used for demand standardisation. For longer droughts, the buffer increases. The implication of this is that, provided the period used for model standardisation of 1961–2012 is representative of long-term conditions, systems with a tick rainfall deficit buffer curve would be resilient to longer duration, lower intensity droughts. This is consistent with the fact that those systems which exhibit the tick shape most strongly are also those with a flat failure boundary curve, that is, systems for which the rainfall deficit triggering the onset of supply-demand deficits is not sensitive to drought duration for periods longer than 12 or 18 months.

An 'oscillating' rainfall deficit buffer curve is indicative of those systems that may be more vulnerable to longer duration, low intensity droughts of the type observed in the historical record. Generally speaking, these correspond to those systems with a stepped failure boundary curve, that is, where the critical rainfall deficit for triggering supply-demand deficits reduces with increasing drought duration.

The metrics presented in this section summarise the drought conditions under which supply-demand deficits start to occur. As such, they provide a partial indication of system resilience across different drought intensities and durations. However, these measures provide no indication of how rapidly supply-demand deficits worsen under increasing rainfall deficit or drought duration once initial failure has occurred. Consideration only of the threshold at which supply-demand deficits are initiated could overstate the sensitivity to drought of those systems where small supply-demand deficits predominate over much of the response surface, such as Wimbleball and Forest and Stroud. This issue is considered further in the next sub-section.

4.3 How do systems respond to longer and/or more severe drought scenarios?

In order to explore this question, the rate at which the proportion of unfulfilled demand increases as a function of rainfall deficit was examined for each system and for each drought duration, as shown by the curves plotted in Figure 4.3. These curves indicate how supply-demand deficits worsen with increasing rainfall deficit for each of the drought durations considered. Essentially, each chart in Figure 4.3 represents a vertical 'slice' across the response surfaces presented in Figure 3.1. Rates of increase in unfulfilled demand with increasing rainfall deficit can be fairly uniform or, more commonly, can become markedly steeper when a particular threshold of rainfall deficit is reached. Typically, this breakpoint corresponds to the position of the 'failure boundary' that was presented and discussed in the previous sub-section.

Assuming the relationship between the proportion of unfulfilled demand and rainfall deficit can be approximated by two linear segments, the rainfall deficit causing a sudden change in rate (the breakpoint) and the rates of increase in unfulfilled demand either side of the breakpoint can be fitted using a two-component piecewise linear regression algorithm (the *piecewise.linear* command from the SiZer R package). The best-fit lines from this exercise are presented in Figure 4.4, and the parameters associated with them are presented in Table 4.1.

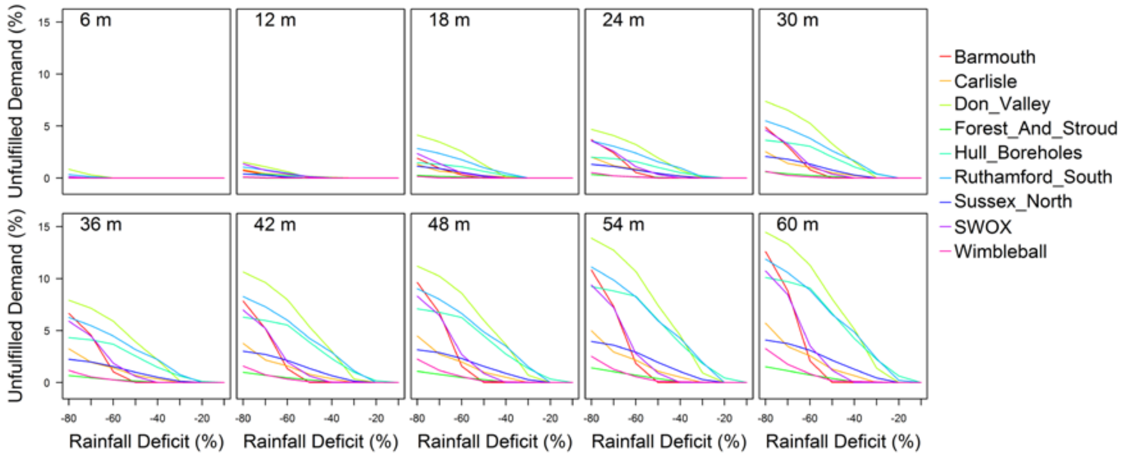

Figure 4.3 Plots of proportion of unfulfilled demand against rainfall deficit, all drought durations (in months)

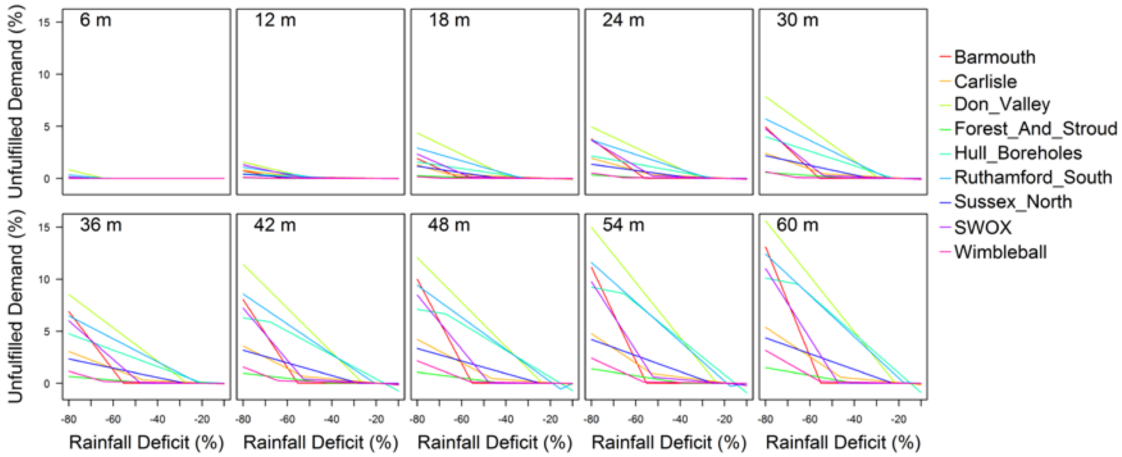

Figure 4.4 Best-fit two-component linear regression lines for unfulfilled demand against rainfall deficit, all drought durations (in months)

Table 4.1 Two-component linear regression parameters

	6 months				12 months				18 months				24 months			
	Bk	*Res*	*R1*	*R2*	*Bk*	*Res*	*R1*	*R2*	*Bk*	*Res*	*R1*	*R2*	*Bk*	*Res*	*R1*	*R2*
Barmouth	N/A	0	0	0	60	0	4	0	60	0.2	10	0	55	0	16	0
Carlisle	75	0	2	0	55	0.1	3	0	65	0.4	6	1	55	0.4	6	1
Don Valley	65	0	5	0	50	0	5	0	40	0	10	0	30	0	10	0
Forest and Stroud	65	0	0	0	65	0	1	0	55	0	1	0	55	0	1	0
Hull Boreholes	60	0	0	0	35	0	1	0	30	0	3	0	25	0	4	0
Ruthamford South	65	0	2	0	45	0	3	0	35	0	6	0	25	0	7	0
Sussex North	70	0	1	0	55	0	2	0	45	0	3	0	35	0	3	0
SWOX	75	0	2	0	55	0.1	5	0	55	0.1	9	0	50	0.2	12	1
Wimbleball	N/A	0	0	0	65	0	1	0	70	0	1	0	65	0.1	3	0

	30 months				36 months				42 months				48 months			
	Bk	*Res*	*R1*	*R2*	*Bk*	*Res*	*R1*	*R2*	*Bk*	*Res*	*R1*	*R2*	*Bk*	*Res*	*R1*	*R2*
Barmouth	55	0	20	0	55	0	28	0	55	0	33	0	55	0	40	0
Carlisle	55	0.4	7	1	45	0.3	8	1	55	0.7	11	2	45	0.5	11	2
Don Valley	30	0	15	0	25	0	16	0	25	0	21	0	25	0	21	0
Forest and Stroud	45	0	1	0	45	0	2	0	40	0	2	0	40	0	3	0
Hull Boreholes	20	0	7	0	20	0.1	8	1	70	5.9	3	11	65	6.7	3	13
Ruthamford South	25	0	10	0	20	0	11	0	20	0	14	0	15	-0.5	15	10
Sussex North	35	0	5	0	25	0	4	0	30	0	6	0	25	0	6	0
SWOX	55	0.3	17	1	50	0	19	0	55	0.4	25	1	45	0	26	0
Wimbleball	65	0.1	4	0	65	0.2	6	0	65	0.2	8	1	55	0.1	8	0

	54 months				60 months			
	Bk	*Res*	*R1*	*R2*	*Bk*	*Res*	*R1*	*R2*
Barmouth	55	0	45	0	55	0	53	0
Carlisle	55	0.9	14	3	45	0.6	14	2
Don Valley	25	0	26	0	20	0	27	0
Forest and Stroud	40	0	3	0	40	0	4	0
Hull Boreholes	65	8.6	4	17	65	9.5	4	19
Ruthamford South	15	-0.3	19	4	20	0.1	20	1
Sussex North	25	0	8	0	25	0	8	0
SWOX	50	0.6	33	2	45	0	34	0
Wimbleball	55	0.1	10	0	55	0.2	12	0

Table notes:
Drought duration (months) is specified in the top header row of the table
Bk breakpoint at which change in slope of best-fit line occurs (expressed in terms of rainfall deficit, to nearest 5%)
Res proportion of unfulfilled demand (%) corresponding to *Bk* (to nearest 0.1%)
R1 slope of best-fit line between 80% rainfall deficit and *Bk* (%), that is to the left-hand side of *Bk* in Figure 4.4
R2 slope of best-fit line between *Bk* and 0% rainfall deficit (%), that is to the right-hand side of *Bk* in Figure 4.4
Shading for cells in Bk column: ≥55% white; 50 to 35% light grey; ≤30%: grey
Shading for *R1*/*R2* cells: ≤5% white; 6–15% light orange; 16–25% orange; ≥26% dark orange

In general, *R1* values are higher than *R2* values, indicating a significant acceleration in the rate of increase in unfulfilled demand with rainfall deficit once a certain threshold (defined by the parameter *Bk*) is reached. This is true for all systems and all durations, except for Hull, where *R2* exceeds *R1* for drought durations of 42 months and longer. This occurs because the threshold that is defined by the parameter *Bk* elsewhere effectively reduces to zero (that is supply-demand deficits occur for any rainfall deficit). In this case, it is *R2*, rather than *R1*, that represents the rate of increase in unfulfilled demand following initial system failure.

With the exceptions of Hull for droughts of 42 months and longer and Ruthamford South for the 48 month drought (an outlier that does not conform even with the other drought durations in the same study system), *R2* is always smaller than 5% regardless of drought duration. Indeed, *R2* is often zero, and therefore represents a situation where there is no supply-demand deficit (that part of the response surface that is coloured grey in Figure 3.1). This suggests that before *Bk* is reached any increase in rainfall deficit will either not cause a supply-demand deficit at all, or will result in only a small increase in the proportion of unfulfilled demand. In other words, the systems remain relatively resilient to increases in rainfall deficit up to the breakpoint *Bk*.

The parameter *Res* represents the proportion of unfulfilled demand that would be expected for a rainfall deficit equal to *Bk*. It therefore provides an indication of the magnitude of additional water resource that would need to be secured to avoid failure for rainfall deficits less than *Bk*. In many cases, *Res* is zero, showing that *Bk* is an indicator of the location of the ‘failure boundary’ discussed in section 4.2. Even when not zero, it is less than or equal to 0.2% for most systems and durations. The main exceptions to this are for droughts of 18 months or longer for Carlisle (*Res* up to 0.9%), for droughts of 30 months or longer for SWOX (*Res* up to 0.6%), and for droughts of 42 months or longer for Hull (*Res* up to 9.5% for the reasons discussed above).

R1 values tend to increase gradually for longer droughts for all systems. This suggests that an increase in rainfall deficit has a proportionally greater effect on the increase in proportion of unfulfilled demand for longer droughts than for shorter droughts. In parallel, *Bk* tends to be located at smaller rainfall deficits for longer droughts. Changes in Bk values with duration reflect the shape of the ‘failure boundary’ curves presented in Figure 4.1.

The resilience of a system can be considered in terms of the combination of *R1* and *Bk* values across the range of drought durations (although, as noted above, the R2 parameter is also of relevance for Hull). The larger the value of *R1* and the smaller the value of *Bk*, the less resilient the system would be, as this implies the development of significantly larger supply-demand deficits at relatively small rainfall deficits for a given drought duration.

Don Valley, Ruthamford South and Hull consistently demonstrate low *Bk* and high *R1* values across much of the range of drought durations considered. This indicates that initial system failure occurs at relatively low rainfall deficits, and that supply-demand deficits worsen significantly with further increases in rainfall deficit beyond this threshold. Hull Boreholes represents the most extreme example of this behaviour in that, for longer droughts, the position of the ‘failure boundary’ represented elsewhere by *Bk* effectively occurs at zero rainfall deficit, and *R2*, rather than *R1*, becomes the parameter representing the rate of increase in unfulfilled demand with rainfall deficits. In Figure 4.3 and Figure 4.4, these systems systematically show the largest proportion of unfulfilled demand compared with other systems, particularly for longer droughts. Sussex North is similar to this group in that it typically exhibits low *Bk* values. However, *R1* values are lower, indicating relatively low increases in unfulfilled demand with increasing rainfall deficit following initial system failure.

SWOX and Barmouth typically exhibit high values of both *Bk* and *R1*. This indicates that these systems are resilient to relatively large rainfall deficits but once the critical deficit threshold is crossed significant supply-demand deficits can develop with increasing rainfall deficits. Carlisle is similar to SWOX and Barmouth, in that it typically exhibits medium to high values of *Bk*, although *R1* values tend to be lower, indicating lesser increases in unfulfilled demand with increasing rainfall deficit following initial failure.

Forest and Stroud and Wimbleball typically have medium to high *Bk* and low *R1* values, indicating that the systems can withstand relatively high rainfall deficits without significant supply-demand deficits occurring and that they worsen only gradually with increased rainfall deficit.

4.4 Discussion

4.4.1 Characteristics of system response to extreme droughts

A number of key points regarding the response of the case study systems to extreme droughts emerge from the presentation of results in this section.

Regarding the circumstances under which supply-demand deficits begin to occur, consideration of the two metrics presented in section 4.2 suggested that, broadly speaking, the case studies exhibit two types of system response:

- **Flat initial failure profile**. The rainfall deficit at which failure commences reduces up to a drought duration of 12 to 18 months, and remains constant for longer durations. These systems tend to be more vulnerable to shorter duration droughts.
- **Stepped initial failure profile**. The rainfall deficit at which failure commences reduces throughout the range of drought durations considered. These systems may be equally or more vulnerable to longer droughts.

Further assessment of the drought response surfaces with piecewise regression was used to characterise the development of these supply-demand deficits with increasing drought duration and intensity following initial system failure. This exercise proved useful in being able to determine a rainfall deficit threshold beyond which significant supply-demand deficits develop, and the rate at which unfulfilled demand increases with increasing rainfall deficit beyond this threshold. These properties were summarised using the regression model parameters *Bk* and *R1*. In general, low values of *Bk* and/or high values of *R1* are indicators of drought vulnerability. Consideration of *Bk* and *R1* values across the range of drought durations enabled three distinct modes of system response to be identified:

- **Progressive failure**. Systems exhibit low values of *Bk* and high values of *R1*, indicating progressive development of supply-demand deficits from quite low rainfall deficits. These systems are sensitive to both drought duration and intensity, and tend to have a stepped initial failure profile. Don Valley, Hull and Ruthamford South fall into this category.
- **Rapid failure**. Systems exhibit moderate to high values of both *Bk* and *R1*. This indicates that systems remain resilient to quite large rainfall deficits across a range of durations, but that supply-demand deficits worsen rapidly with increased rainfall deficits once failure is initiated. These systems tend to have a flat initial failure profile. Barmouth and SWOX fall into this category.

- **Lower sensitivity**. Systems exhibit moderate to high values of *Bk*, and low values of *R1*. Supply-demand deficits may occur, but remain small for all but the most severe droughts considered. Initial failure profiles are stepped or poorly defined, but are of minimal relevance because supply-demand deficits do not increase significantly with increased rainfall deficit. Forest and Stroud and Wimbleball fall into this category.

The remaining two systems exhibit behaviours that are intermediate between the three basic responses identified above. Carlisle exhibits relatively high values of *Bk*, but lower values of *R1* than Barmouth or SWOX, and sits between the rapid failure and lower sensitivity types. Sussex North exhibits relatively low values of *Bk* and *R1* and represents an intermediate case between the progressive failure and lower sensitivity types.

4.4.2 Can the response be explained in terms of system characteristics?

Based on the results of the nine case studies, it appears that a broad distinction can be made between systems that are sensitive to single season droughts and those that are sensitive to multi-season droughts. Those systems that exhibited a flat initial failure profile and a rapid failure drought response are examples of single season systems, most notably Barmouth and SWOX. In these systems, the intensity of the 12 to 18 month drought is the key indicator of system sensitivity to drought. Generally speaking, if a system of this type can withstand a certain rainfall deficit over a duration of 12 to 18 months, it can withstand the same rainfall deficit indefinitely. This arises because potential winter inputs under average conditions are large relative to storage capacity, and full refill can still occur each year under quite large rainfall deficits. The most extreme example of this type of system among the nine case studies is Barmouth, where results indicate that a 50% rainfall deficit can be supported for all durations up to the maximum 60 months considered in this study.

Nevertheless, when systems of this type do fail, supply-demand deficits can develop rapidly because system demands are relatively large compared to storage capacity, leading to rapid depletion of remaining storage.

Multi-season systems typically demonstrate a stepped initial failure profile and a progressive failure response. Case studies exhibiting these characteristics most strongly included Don Valley, Hull and Ruthamford South. These systems tend to fail at lower rainfall deficits for multi-year droughts. This typically occurs because these systems have relatively large storage relative to the magnitude of winter inputs and system demands, such that system storage is gradually depleted over successive drought years for longer drought events, even if rainfall deficits are relatively small.

The case study results also suggest that conjunctive use supply systems are generally more resilient to drought than those relying on a single reservoir or aquifer resource. Consequently, while the drought response exhibited by Carlisle is similar in some respects to the single season, rapid failure responses exhibited by single reservoir systems like Barmouth and SWOX, it tends to be more resilient because Castle Carrock Reservoir is supplemented by abstraction from the River Eden.

Though Sussex North exhibits a similar progressive failure response to systems like Don Valley and Hull, the proportion of unfulfilled demand across the response surface is generally lower because supplies are drawn from a variety of different sources, including run-of-river abstraction, groundwater, reservoir storage and imports from other resource zones. Furthermore, it should be noted that, although the modelling presented herein has suggested that the Don Valley and Hull case studies are sensitive to droughts across a range of durations and at quite low intensities, these systems are in reality part of a much larger integrated resource zone, the Yorkshire Grid. Therefore, while their representation as standalone systems in this project has been instructive in terms of demonstrating drought sensitivities across a range of supply system types, they are likely to be much more resilient to drought when operated as part of the Yorkshire Grid.

Of the nine case studies, those that proved to be most resilient to extreme droughts were Wimbleball and Forest and Stroud. The common characteristics shared by these systems is that supplies are sourced from rivers with large upstream catchments in high rainfall regions and in which low flows are supported by releases from reservoirs in the headwaters, in addition to local groundwater resources. Carlisle is also similar in this respect, in that a relatively small surface reservoir is supplemented by abstractions from a large river in a high rainfall area and with significant lake storage to support baseflows in the upstream catchment.

5 Conclusions and recommendations

5.1 Conclusions

5.1.1 Introduction

The specific objectives of this study as stated in section 1.2 were as follows:

- to assess the impact of a range of drought scenarios on a variety of water supply systems
- to present the comparative sensitivity of systems to drought and identify reasons for failure
- based on these assessments, to investigate whether it would be possible to identify a generalised typology of supply system sensitivity to drought that could be applied to all systems to draw inference on risk to supply from drought

The extent to which the project has achieved these objectives is discussed below.

5.1.2 Objective 1 – Assessment of drought impacts

The approach that has been developed during this project provides a powerful set of tools for assessing the response of systems with differing characteristics to extreme drought. The drought sensitivity framework provides a means by which drought impacts on systems with different climatological characteristics can be compared in a rigorous and consistent manner with a relatively small number of scenario runs. The development of integrated system response metrics and their presentation using drought response surfaces allow the results of the drought sensitivity modelling to be summarised in an effective manner. The piecewise regression approach used for the assessment of response surfaces facilitates further comparison of system drought responses.

5.1.3 Objective 2 – Analysis of comparative drought sensitivity

Results from the nine case studies have yielded valuable insights into how the case study systems respond to droughts that are more extreme than those observed in the historical record. In particular, the case study results suggest that systems with a single season response tend to be most sensitive to short duration droughts (12 to 18 months). Although the systems tested remained resilient to quite large rainfall deficits, supply-demand deficits can develop rapidly once the drought intensity threshold at which initial failure occurs is crossed.

In contrast, systems with a multi-season response may be sensitive to a range of drought durations, including multi-year droughts. Failure can occur at quite low rainfall deficits, particularly for longer durations, but supply-demand deficits tend to develop more gradually with increasing drought intensity.

Conjunctive use systems drawing from a diverse range of sources tend to be more resilient than systems based on a single source or group of sources with similar characteristics (for example a group of boreholes abstracting from the same aquifer unit, or a cascade of upland reservoirs). The most resilient systems tested in this project tended to be those where local reservoir or groundwater resources were supplemented by abstractions from large rivers with high rainfall and baseflows that are supported by natural catchment storage or artificial river regulation.

5.1.4 Objective 3 – Drought sensitivity typology

Although the model results suggest that key distinctions can be made in terms of supply system sensitivity, it is also clear that systems with quite different characteristics can yield similar drought responses. For instance, Barmouth, a small water resource zone comprising an upland gravity-fed reservoir in mid-Wales, and SWOX, a large zone which is largely based on a pumped storage reservoir in lowland England, yield similar drought responses. Conversely, Ruthamford South, another large water resource zone based around a pumped storage reservoir in lowland England yields a quite different drought response to SWOX.

It has not therefore proved possible, based on the nine case studies presented here, to develop a generalised typology of drought response that could be applied to other systems without a requirement to model each of the systems to the level of detail in this study. This is in part because of the small sample from which to draw conclusions and partly because a system’s response is the result of a complex interplay of many different system-specific characteristics, including climate, catchment characteristics, infrastructure characteristics, demand and licence constraints. In order to determine whether the development of a generalised typology would be possible, a much more comprehensive analysis across a multitude of system combinations would be required.

5.1.5 Limitations of the method

Two important limitations should be noted regarding the representation of the case study water supply systems used in this study. As noted in section 2.2, it should be stressed that the aim of the modelling was to develop case studies that were considered broadly representative of the diversity of water supply system types found in England and Wales. Consequently, the aim of the relatively simple modelling carried out in this study was to replicate the key characteristics of the case study systems, rather than reproduce the level of operational detail that would be incorporated within water company water resources planning models. Furthermore, as discussed in section 4.4.2, in some cases only selected elements of larger integrated water resource zones were modelled. This is the case for Don Valley and Hull, for example. Therefore it should be stressed that the drought responses presented for the case studies in this report may not necessarily reflect the actual response of the real supply systems under extreme drought conditions.

5.2 Recommendations

5.2.1 Potential applications

The drought sensitivity framework approach set out in this document has a wide range of potential applications in water resources planning, including:

- as an options appraisal tool, for instance to look at the relative benefits of drought management options, or to assess the impact of infrastructure changes or licence sustainability reductions on resilience to drought

- as a screening tool to examine the implications of improved evidence on drought likelihood from the historical record, or to assess likely impacts of future climate change on system resilience

5.2.2 Recommendations for further work

It is recommended that guidance is developed for water companies on how the sensitivity approach could be used to support the water resource and drought planning processes. Furthermore, in order to promote wider application and further refinement of the approach, it is recommended that further research is also carried out to:

- incorporate spatial coherence into drought scenarios for application to larger water resource zones or for regional water resources planning
- test the drought sensitivity framework to assess the relative importance of temperature, and in turn evapotranspiration, when synthetically creating droughts
- compare the drought scenario framework approach with other synthetic drought methodologies to understand the benefits of different methods
- further explore drought resilience in conjunctive use systems (the finding that they are generally more resilient suggests that not only is there a deployable output benefit from conjunctive use but that there is an additional resilience benefit too, and the reasons behind this should be explored further)
- assess the degree to which system operating rules influence drought resilience
- further investigate the drought sensitivity groundwater supply systems, including infrastructure constraints such as borehole depth
- consider application of the method to other sectors (for example agriculture or hydropower) and to factors other than drought

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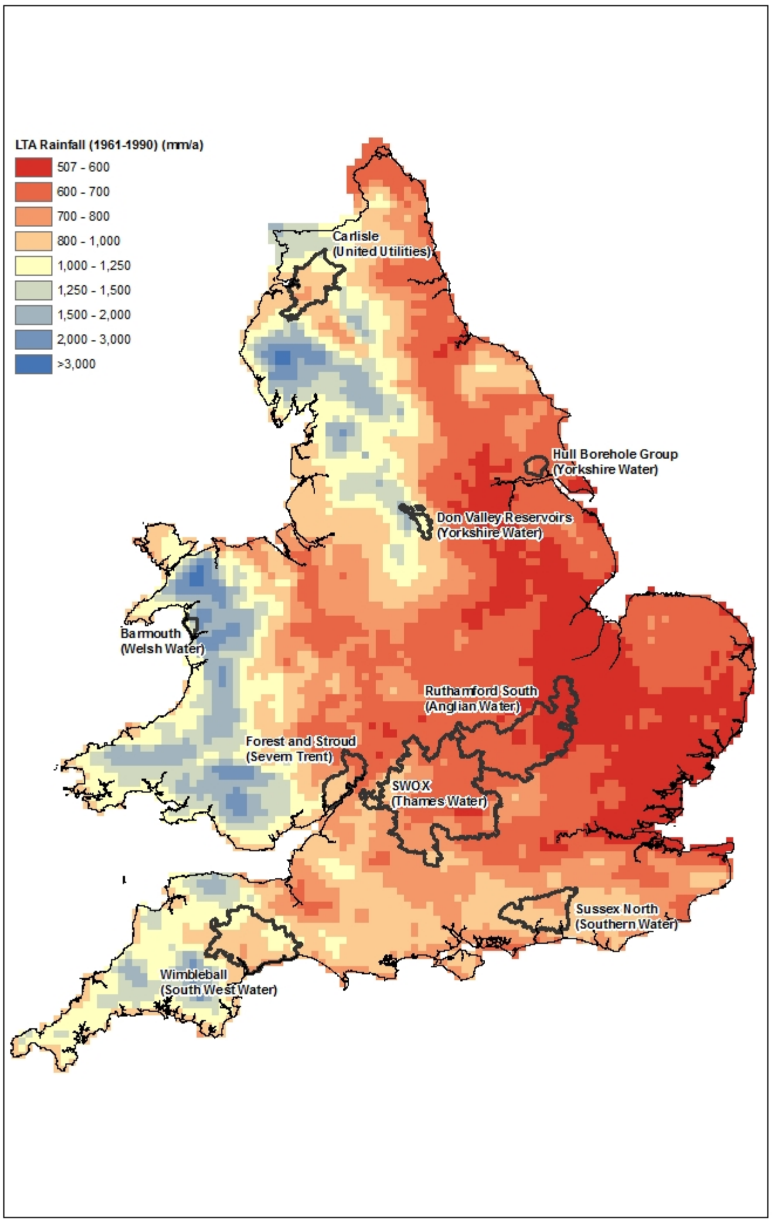
Appendix A: Case study factsheets

Performance of water supply systems during extreme drought

Case study fact sheets

This document provides an overview of model representation for, and results from each case study supply system. Each fact sheet provides a brief description of the system and the approach to modelling, a schematic highlighting the different system components and a drought response surface plot. The response surface plot shows for each drought scenario (described below), the total unfulfilled demand as a proportion of the total requested demand during the drought for a range of drought durations and rainfall deficits. Historical rainfall deficits from the observed rainfall record (1961–2012) are plotted as black stars.

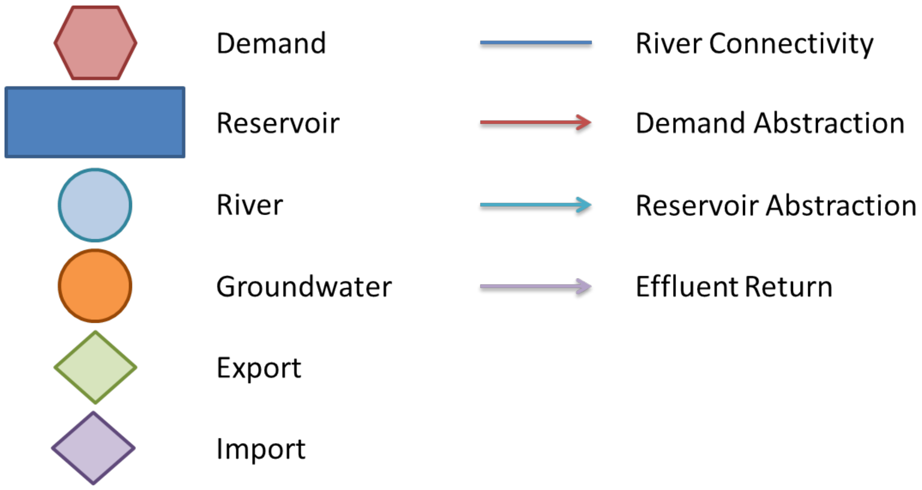
Case study locations



Drought scenario overview

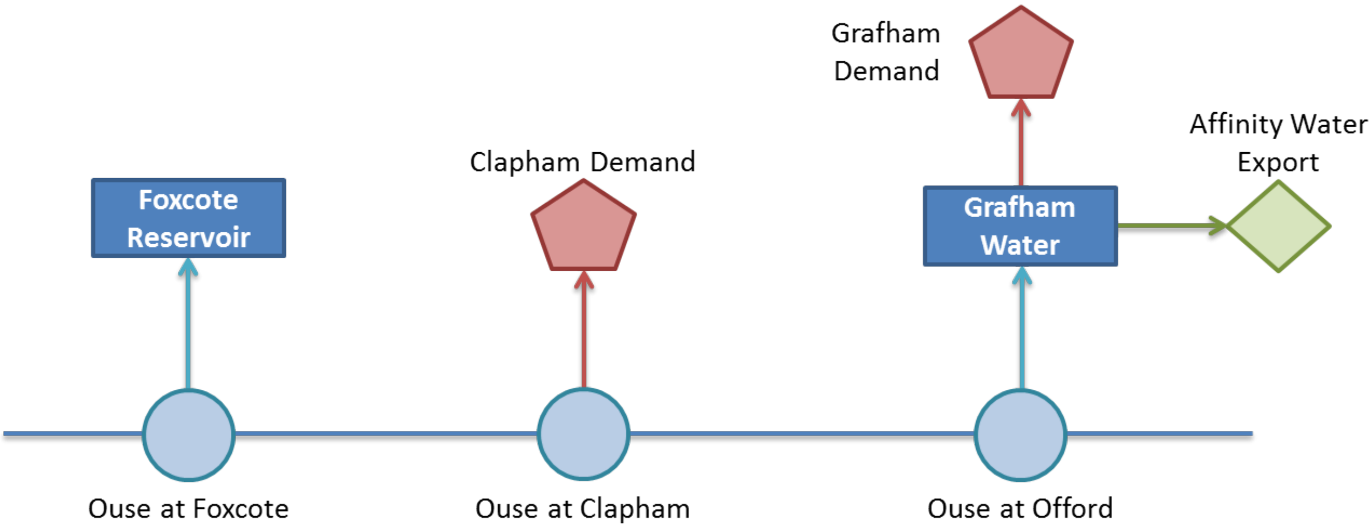
ProfApril	Drought begins in April with a flat profile expressed as a deficit of the long-term average rainfall
ProfOctober	Drought begins in October with a flat profile expressed as a deficit of the long-term average rainfall
ProfSummer	Drought begins in April with a sine profile around ProfApril to accentuate the summer deficit
ProfWinter	Drought begins in October with a sine profile around ProfOctober to accentuate the winter deficit

Key to water resource zone systems diagrams

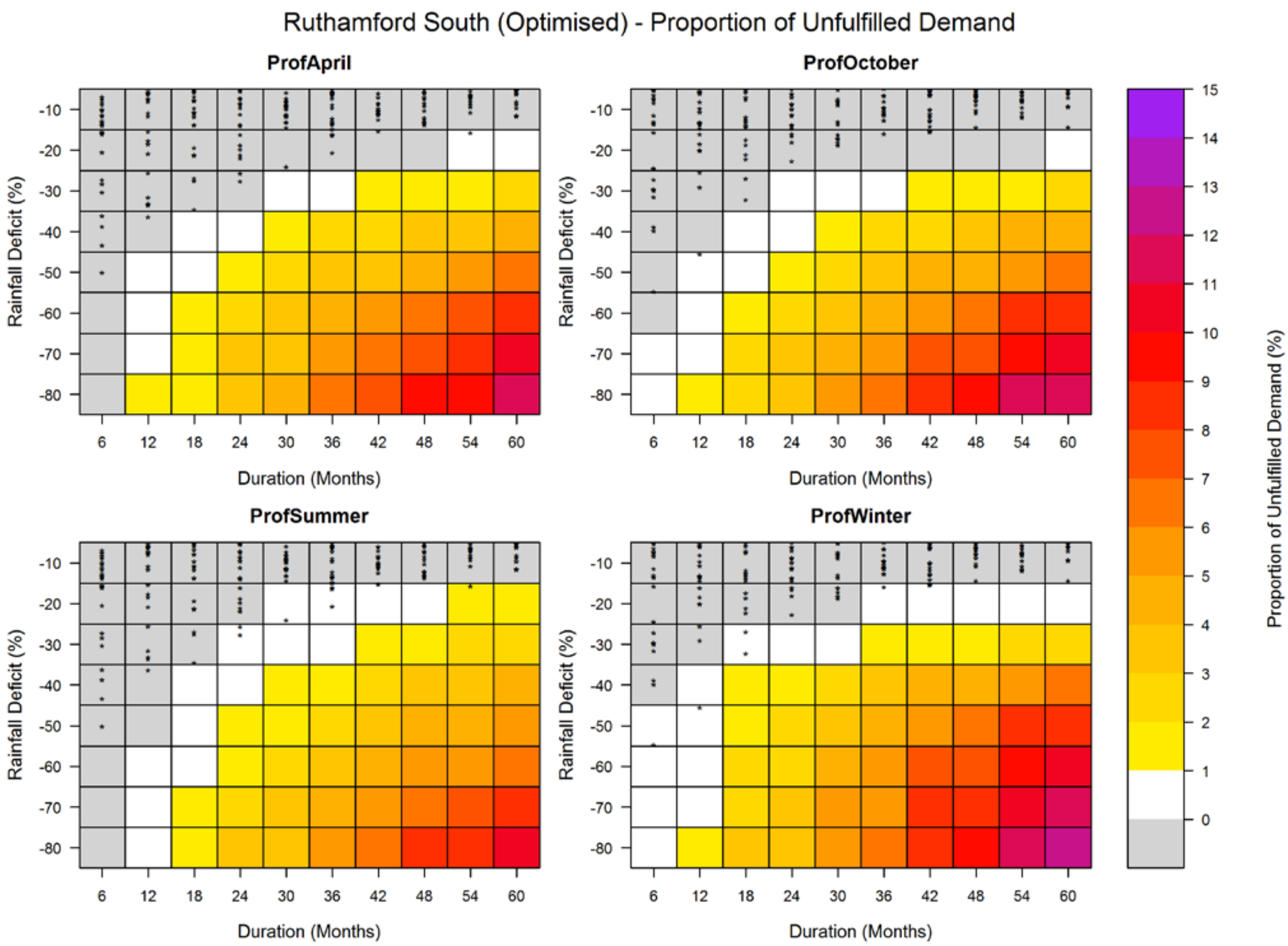


Anglian Water – Ruthamford South

The Ruthamford South Water Resource Zone comprises the River Ouse, which is used for direct public water supply at Clapham and as the source for Grafham Water. Grafham Water is a large pumped storage reservoir used for public water supply by both Anglian Water and Affinity Water. The River Ouse is heavily influenced by effluent returns from Milton Keynes, which help support abstractions from the river. A hydrological model has been developed for the River Ouse abstractions. There are groundwater sources in the zone which are not considered to be drought vulnerable and have therefore not been included for this case study.

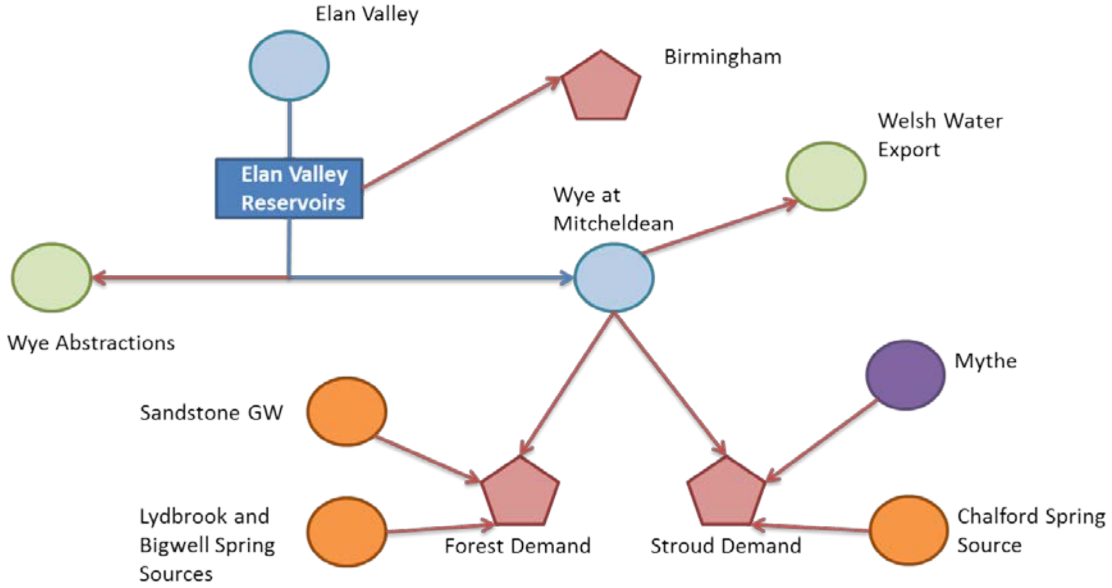


Drought sensitivity surface

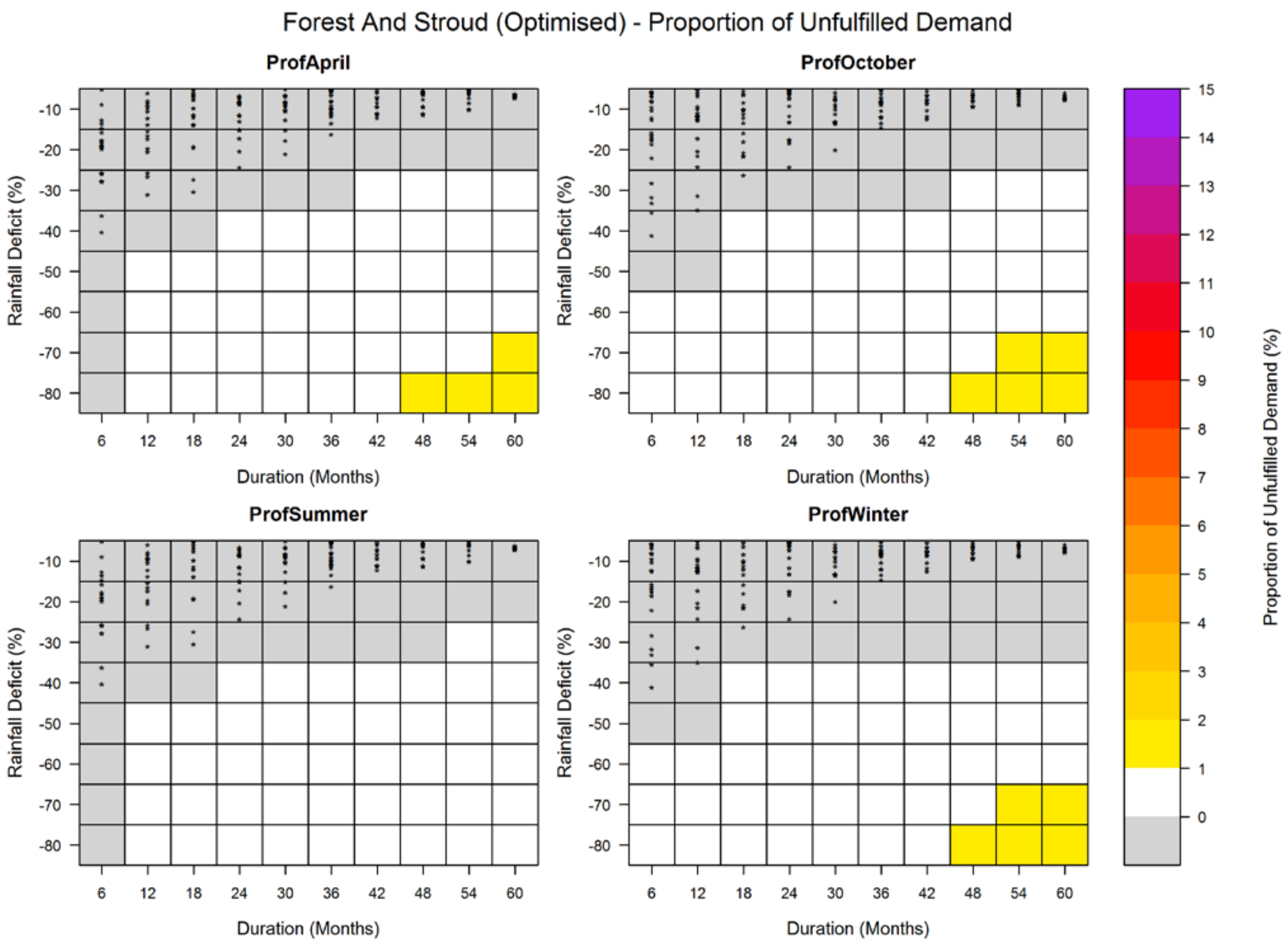


Severn Trent Water – Forest and Stroud

Forest and Stroud is a conjunctive use water resource zone comprising a series of spring and groundwater sources and an abstraction from the River Wye. The River Wye is regulated from the Elan Valley reservoirs and the abstraction at Mitcheldean is modest compared with the volume of river flow. The zone has been represented as two demand nodes which are both supplied by the River Wye and each supplied by local spring sources.

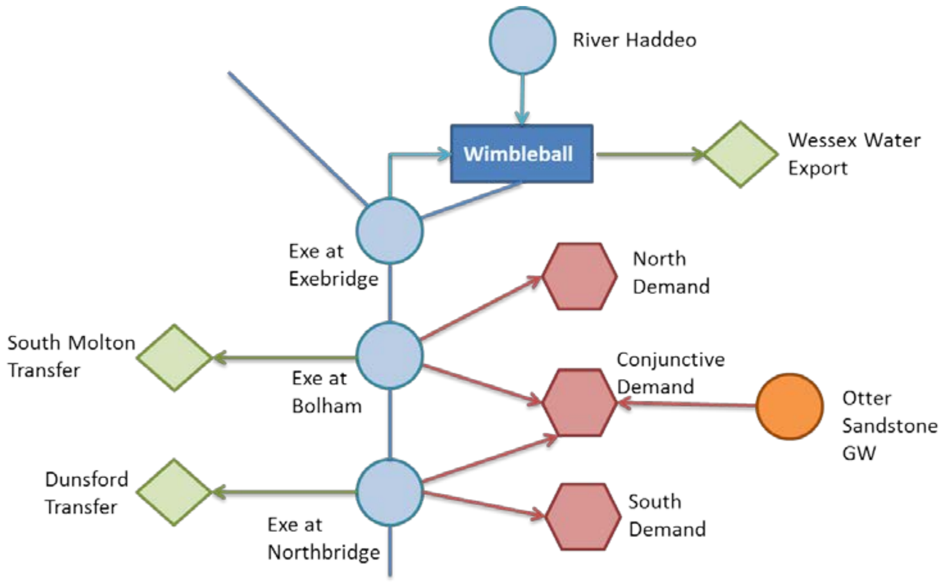


Drought sensitivity surface

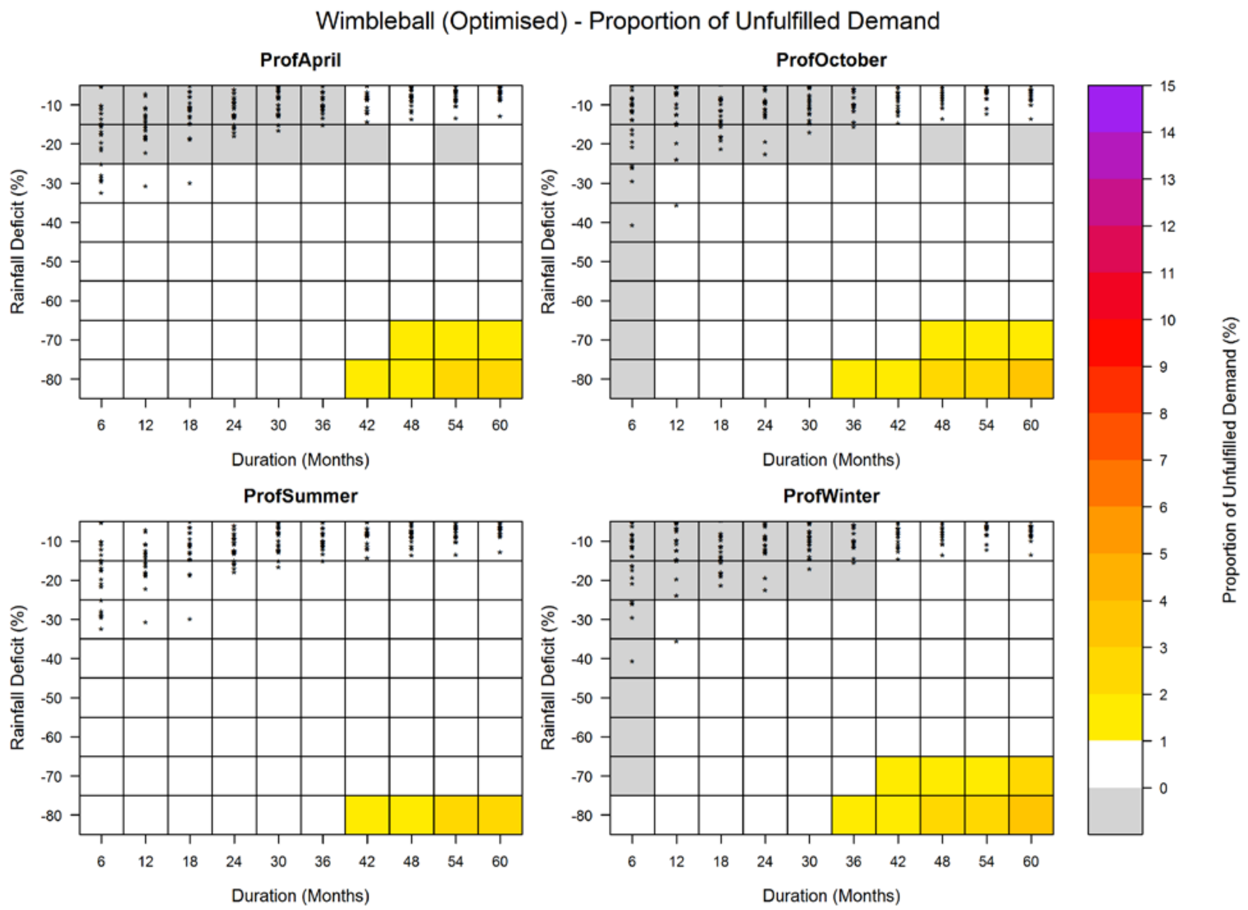


South West Water – Wimbleball

Wimbleball is a conjunctive use water resource zone with sandstone groundwater sources and river abstractions from the River Exe. Abstractions from the River Exe are supported during lower river flow periods through releases made from Wimbleball Reservoir. Wimbleball Reservoir has an augmentation scheme allowing for pumped winter refill from the River Exe. Hydrological models have been developed for Wimbleball inflows and the River Exe. The representation of the Otter groundwater sources is based on expert judgement of groundwater operations and performance during drought.

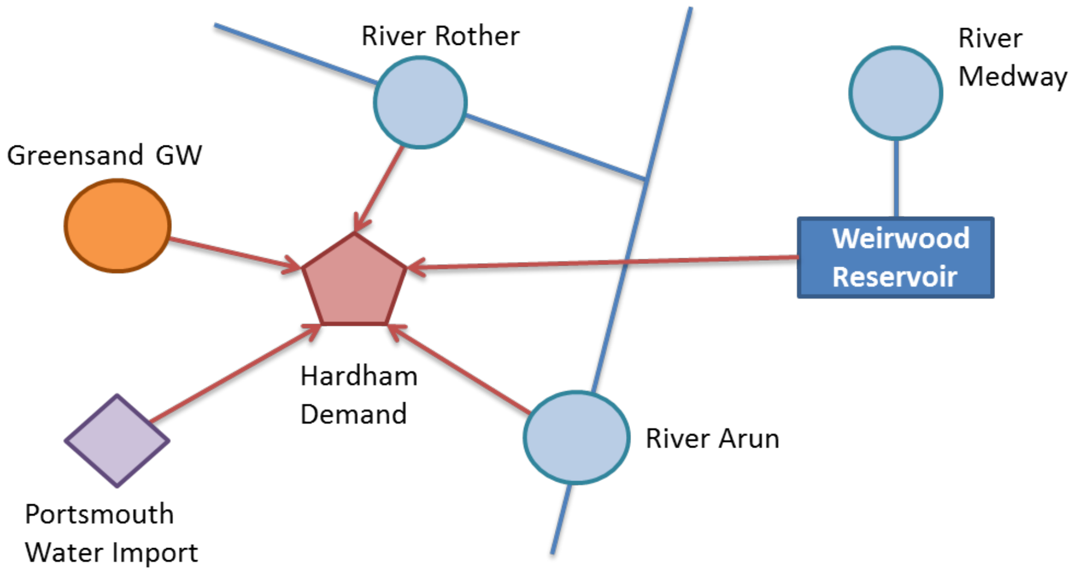


Drought sensitivity surface

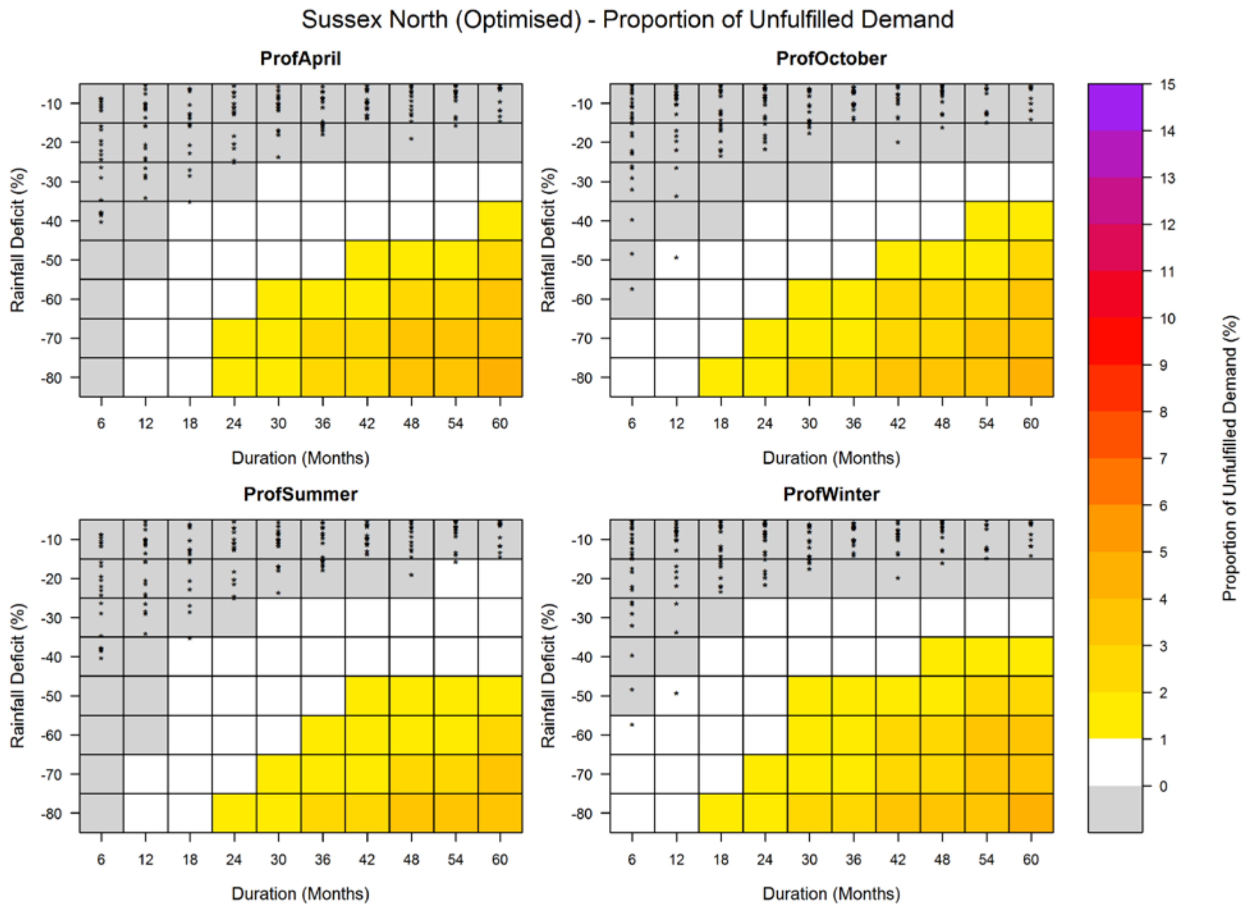


Southern Water – Sussex North

The primary source of water supply for the Sussex North Water Resource Zone is the River Rother. Further resources are available from the Lower Greensand aquifer, Weirwood Reservoir and an import from Portsmouth Water. There is also a new source of abstraction from the River Arun which allows abstraction to a small bankside reservoir. The case study has been constructed using hydrological models for the River Rother and River Medway and a groundwater model for the greensand aquifer. The remaining resources are implemented using operational rules.

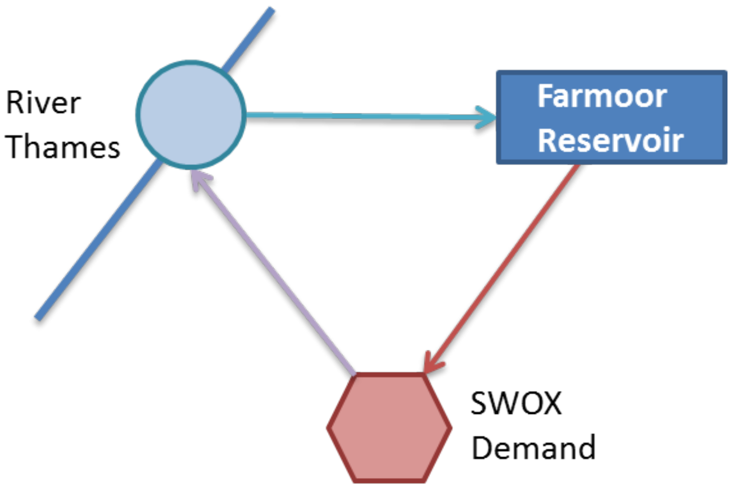


Drought sensitivity surface

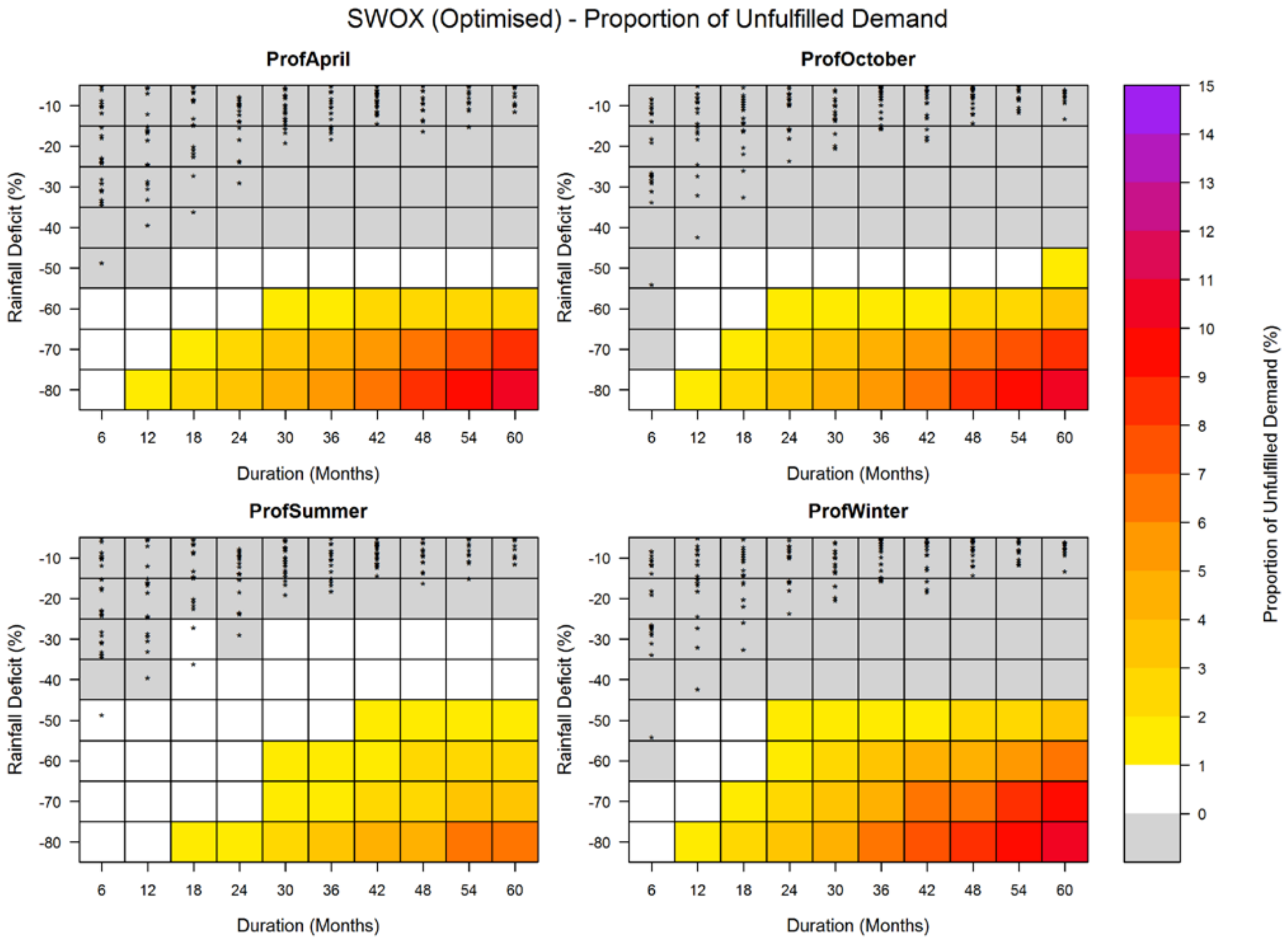


Thames Water – Swindon and Oxford (SWOX)

The Swindon and Oxford Water Resource Zone is a conjunctive use system with abstraction from the River Thames to Farmoor Reservoir and groundwater abstractions from both chalk and limestone aquifers. For this case study groundwater has not be included because Farmoor Reservoir is the drought-critical resource. A hydrological model has been calibrated for the River Thames and Farmoor Reservoir has been implemented to reflect its operation during drought periods.

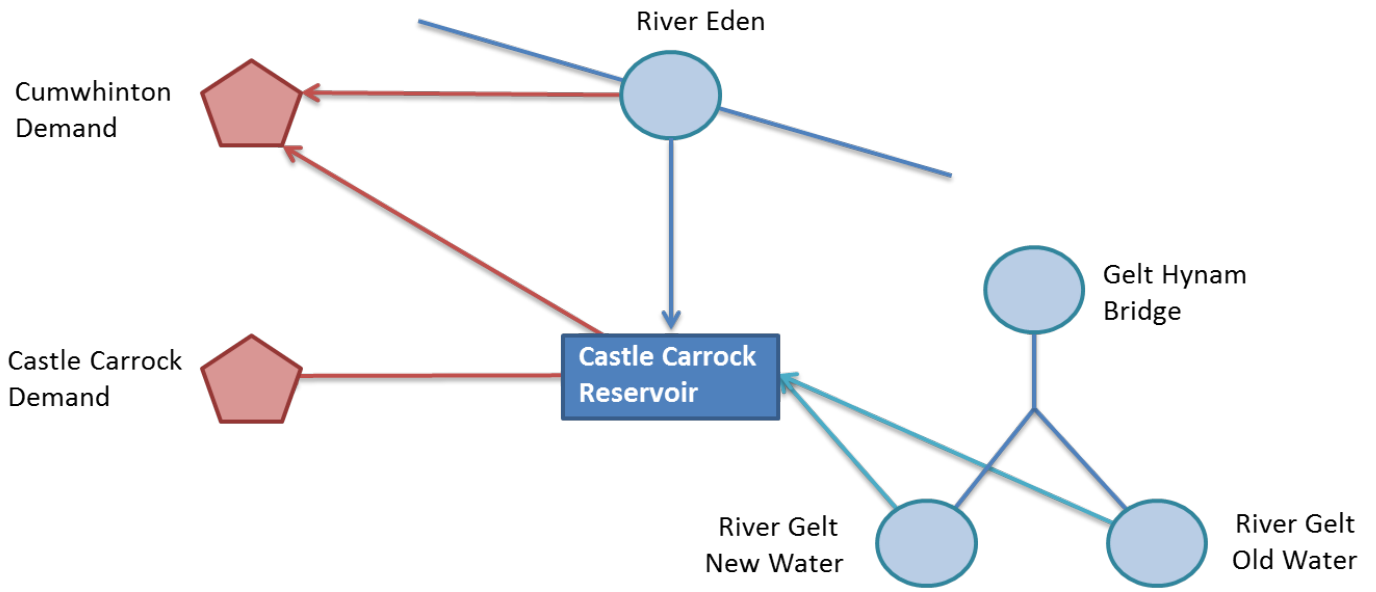


Drought sensitivity surface

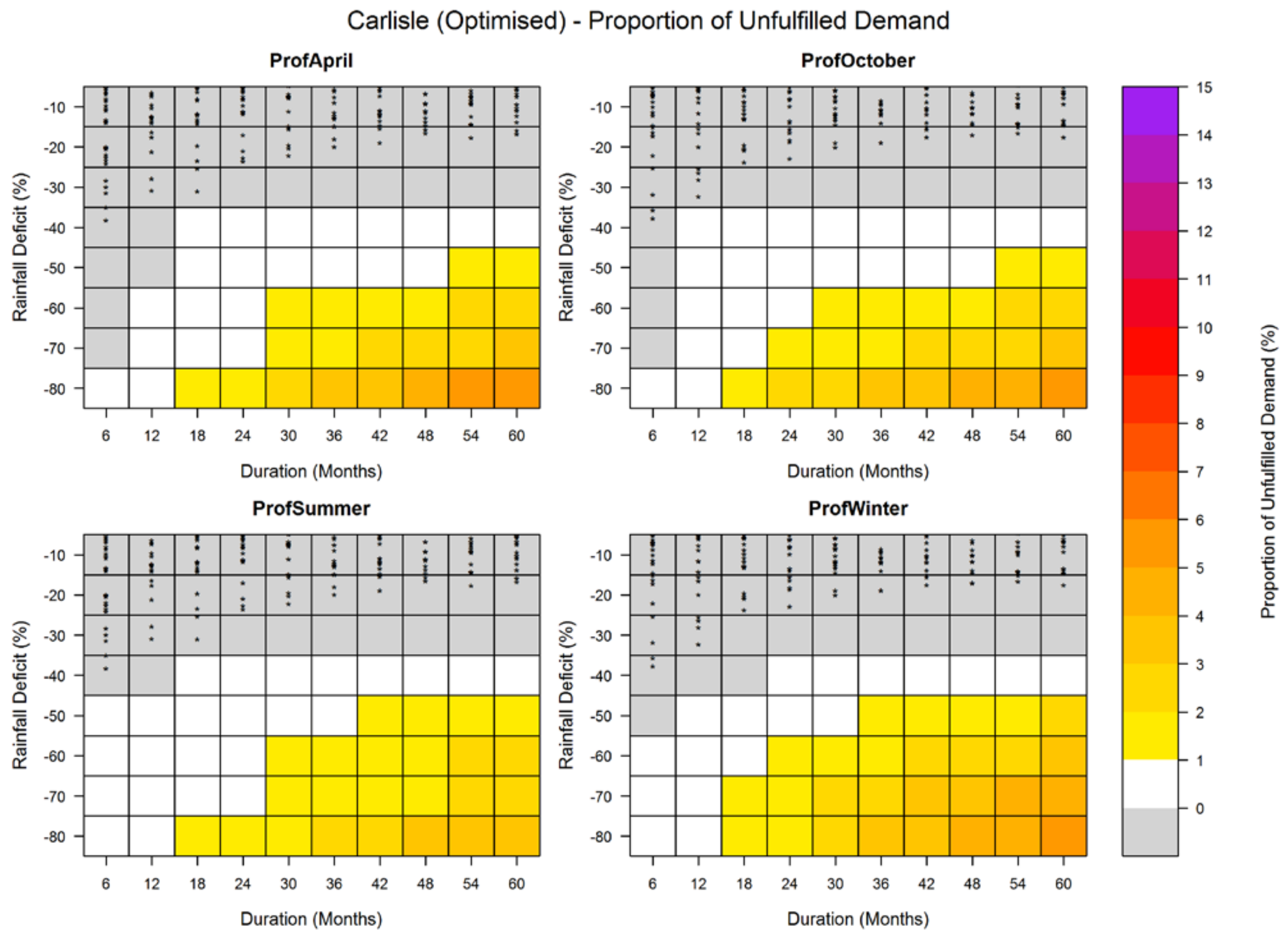


United Utilities – Carlisle

The main resources in the Carlisle Water Resource Zone are the direct abstraction from the River Eden, and Castle Carrock Reservoir which is supplied by the River Gelt. The River Eden abstraction is small compared with the volume of the river and can be used to provide additional resource to Castle Carrock in times of drought. The supply system model includes two demand nodes, both of which take resource from Castle Carrock, making it the critical resource in the system.

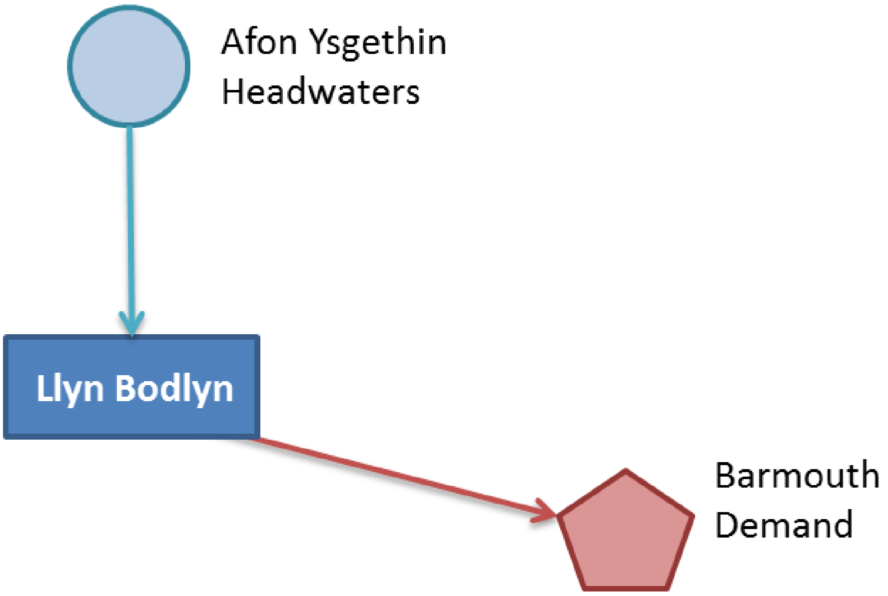


Drought sensitivity surface

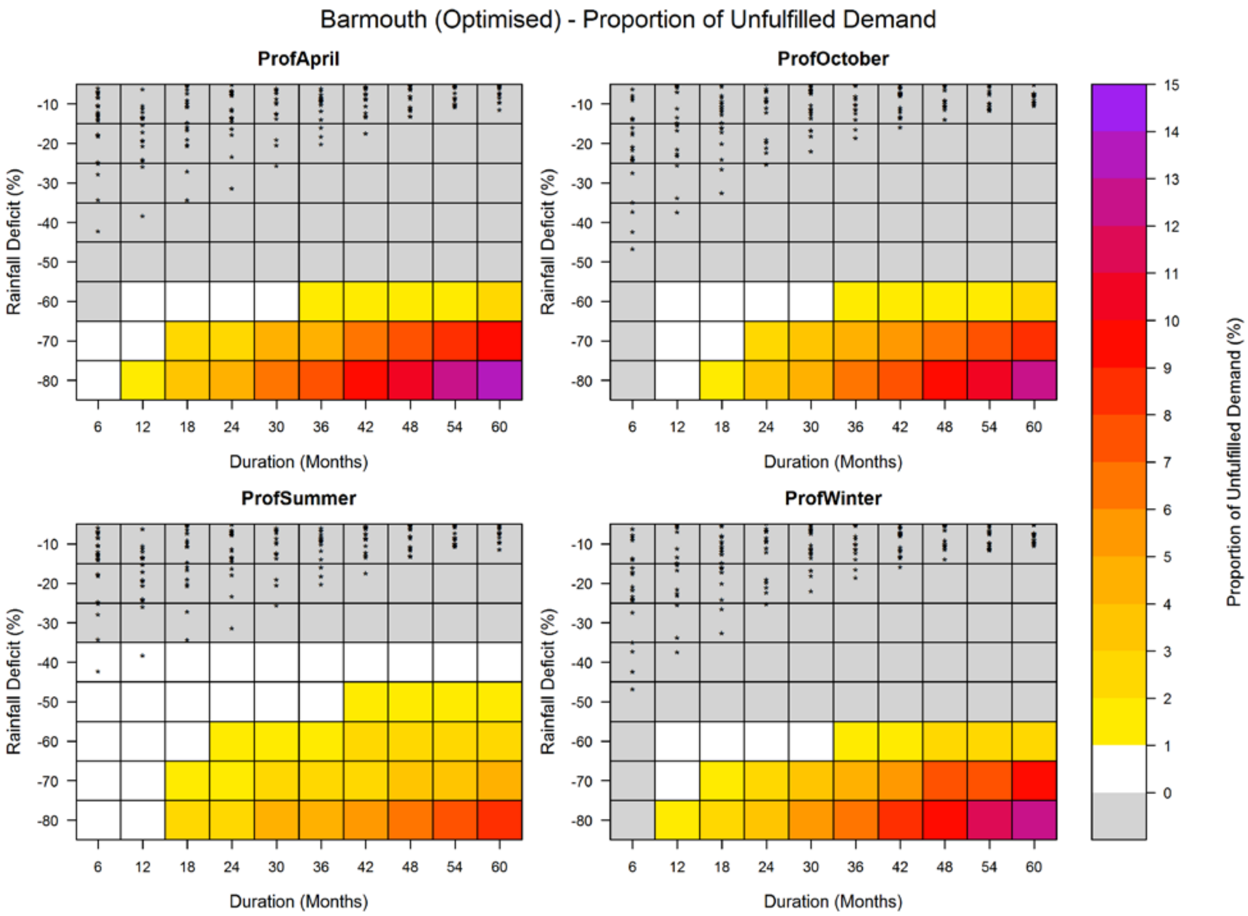


Welsh Water – Barmouth

Welsh Water's Barmouth Water Resource Zone draws its supply from Llyn Bodlyn reservoir, which is a small gravity-fed upland reservoir. The reservoir is used directly for public water supply to Barmouth. A hydrological model has been calibrated to provide the inflows to Llyn Bodlyn.

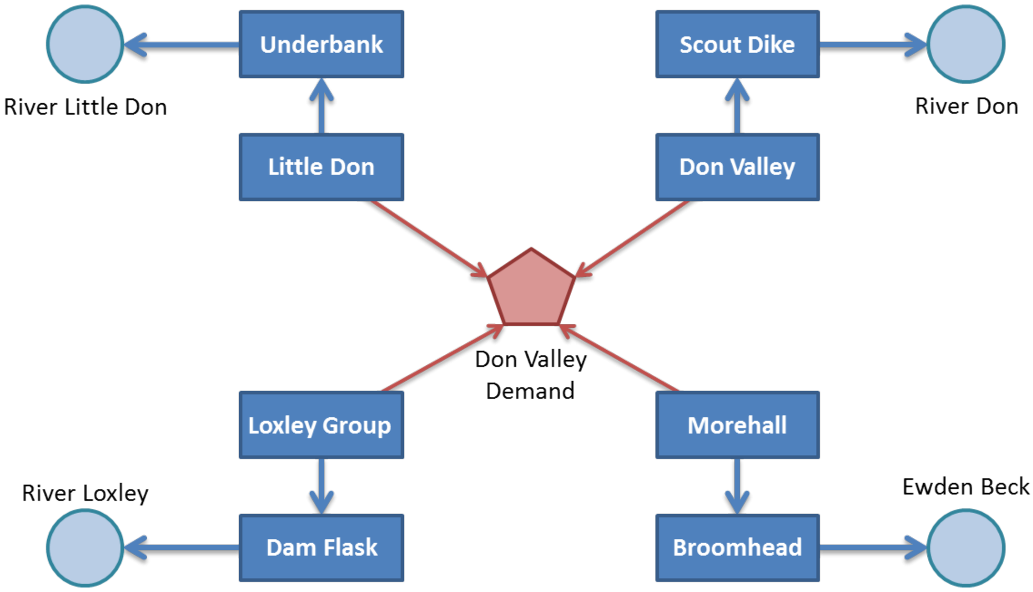


Drought sensitivity surface

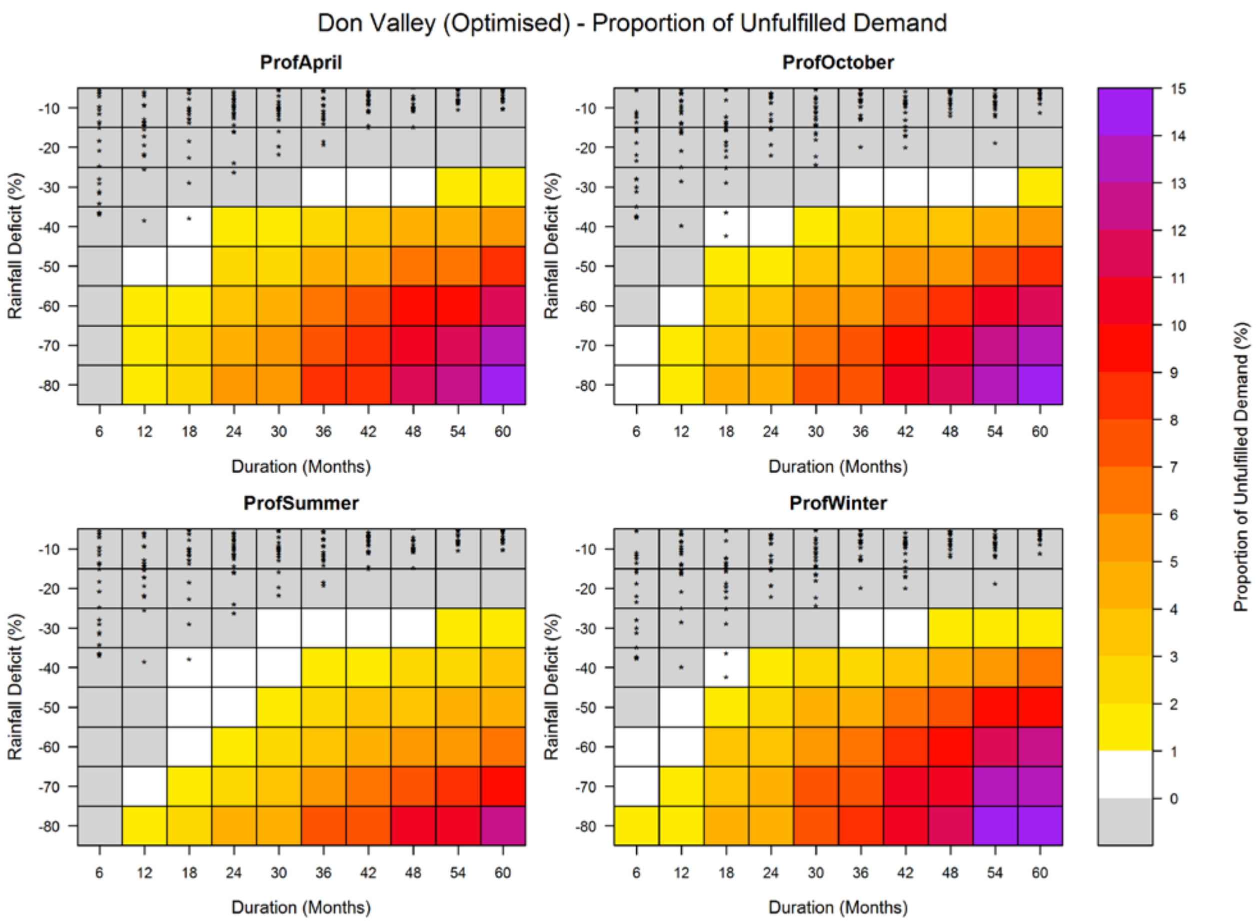


Yorkshire Water – Don Valley reservoirs

The Yorkshire Water Grid Water Resource Zone covers a large area with high levels of interconnectivity and conjunctive use. The Don Valley reservoirs form one component of the grid system, but have been modelled as a standalone case study for this project. This results in increased reservoir drawdown where, in practice, other conjunctive sources would be used for public water supply in the grid. The reservoirs operate as grouped pairs with the upstream reservoir used for public water supply abstraction and a downstream reservoir providing a compensation release. Hydrological models have been calibrated to provide inflows for each reservoir.

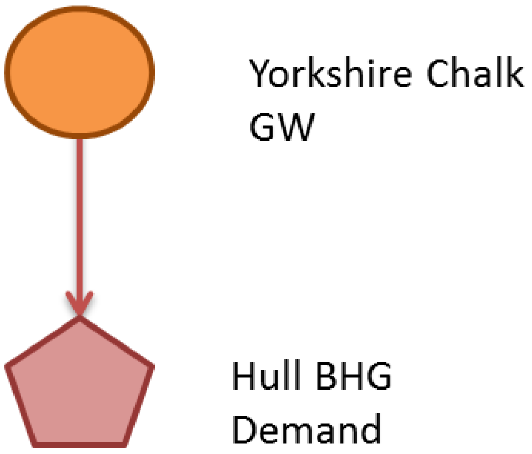


Drought sensitivity surface

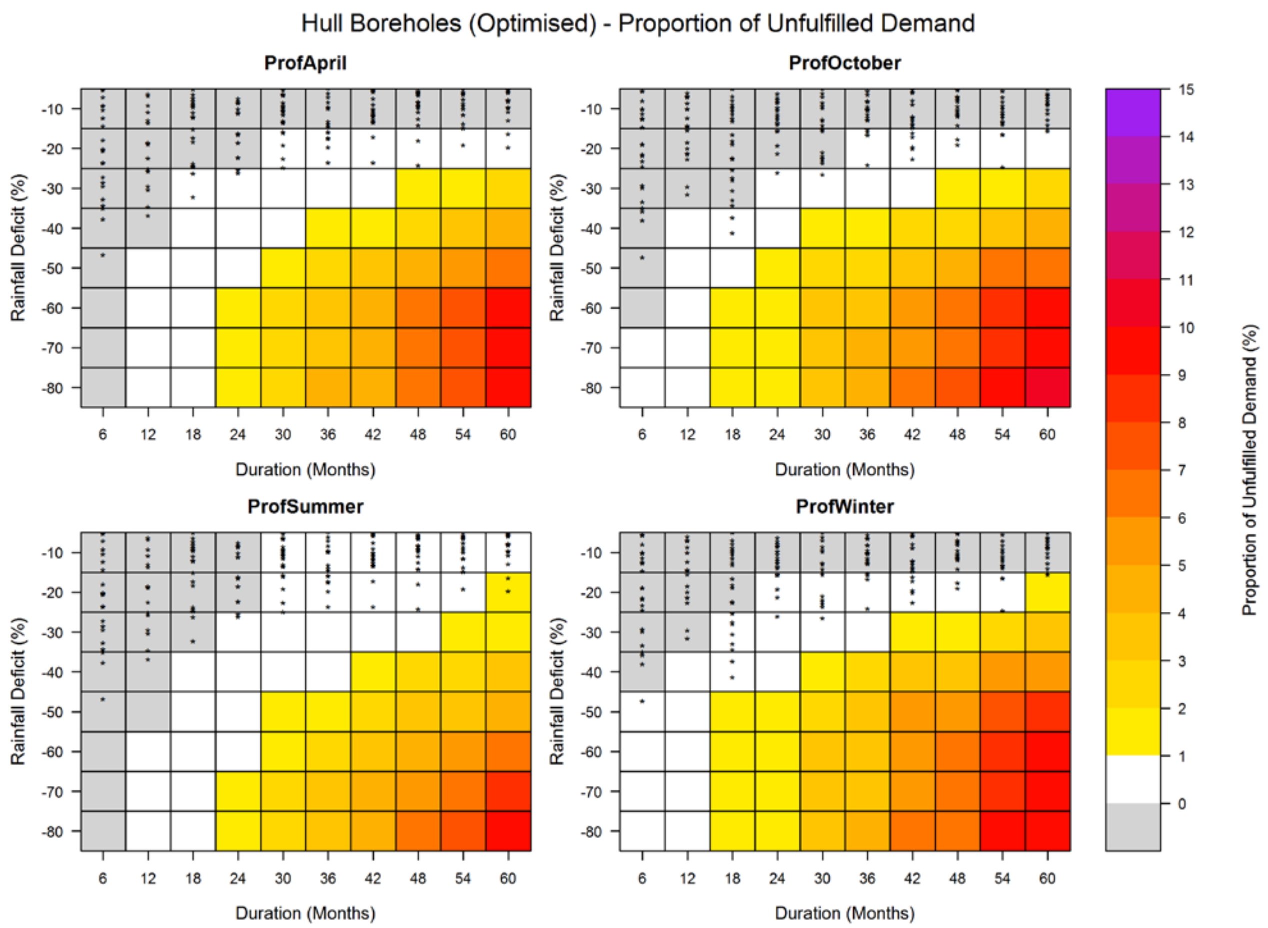


Yorkshire Water – Hull Borehole Group

The Hull Borehole Group is another component of the highly interconnected Yorkshire Water Grid. The four groundwater sources in the group abstract from the Yorkshire chalk aquifer, which is overlain by glacial till at the borehole locations. A simple model has been constructed in which the group is represented as a reservoir with inflows (e.g. recharge, vertical leakage) and outflows (e.g. abstraction, river baseflow). The group has been modelled as a standalone case study separate from the grid, with the input demand profile based on monthly average historical abstraction. Abstraction rates are controlled as a function of aquifer storage as control lines are crossed.



Drought sensitivity surface



Appendix B: Standardisation of system performance

B.1 Why standardise demands?

Each case study was initially constructed with information provided by the water company partners. This process typically involved a discussion as to how different demand centres could be grouped together while still ensuring the sources were being utilised in a realistic manner. In the water supply system model the demand centres are represented as a single demand value which is then factored by a monthly demand profile to account for variations in demand throughout the year. The demand values that were provided by the water companies represented a range of different demand scenarios from the actual system demand, the water resource zone deployable output or the source yield. This means that the water supply system models were originally constructed representing different types of demand scenario.

In addition, the water company supplied demands have been calculated using their own in-house models and methods which have different assumptions to the case study models constructed for this project. These differences include different input climatology, different hydrology and hydrogeological models, and different (more complex) representation of the water supply system. Therefore, the demands that have been provided may not be wholly representative of the newly constructed case study models.

Lastly; each water company operates to a different level of service (LoS), which is dictated by a number of factors such as customer attitudes, the historical droughts a system has experienced, the reliability of sources and the company attitude towards risk. The LoS of a water resource zone will influence the performance of the water supply system during drought. However, in order to compare the physical system performance between different companies, removing LoS allows a fairer comparison.

Taking account of these factors, the water supply system demands were standardised in order to allow a better comparison of the case study water supply models to the drought scenarios.

B.2 Standardisation method

In order to standardise the demand placed on each water supply model the maximum demand that could be taken without the system entering into a supply-demand deficit was calculated. This identifies the critical drought for a given system and increases the demand on the system until it reaches a point where any additional demand would cause it to fail. For all case study systems this was undertaken for a period of 1961–2012. The method of undertaking this procedure is outlined below and varies depending on the number of demand nodes that are in the water supply system model.

B.2.1 Models with single demand nodes

For the case study models with just a single demand node (Barmouth, Don Valley, Hull, Sussex North, SWOX) a binary search algorithm was used to identify the maximum supply system demand. This algorithm can be equated to a game of ‘higher or lower’, where a maximum and minimum search boundary are set and the model is run with the boundary values and a central value. Depending on the success or failure of the supply-demand balance of the water supply system model two of the three values are taken forward to form the new upper and lower boundary for the next iteration. An example of this procedure for the SWOX case study can be seen in Figure B.1.

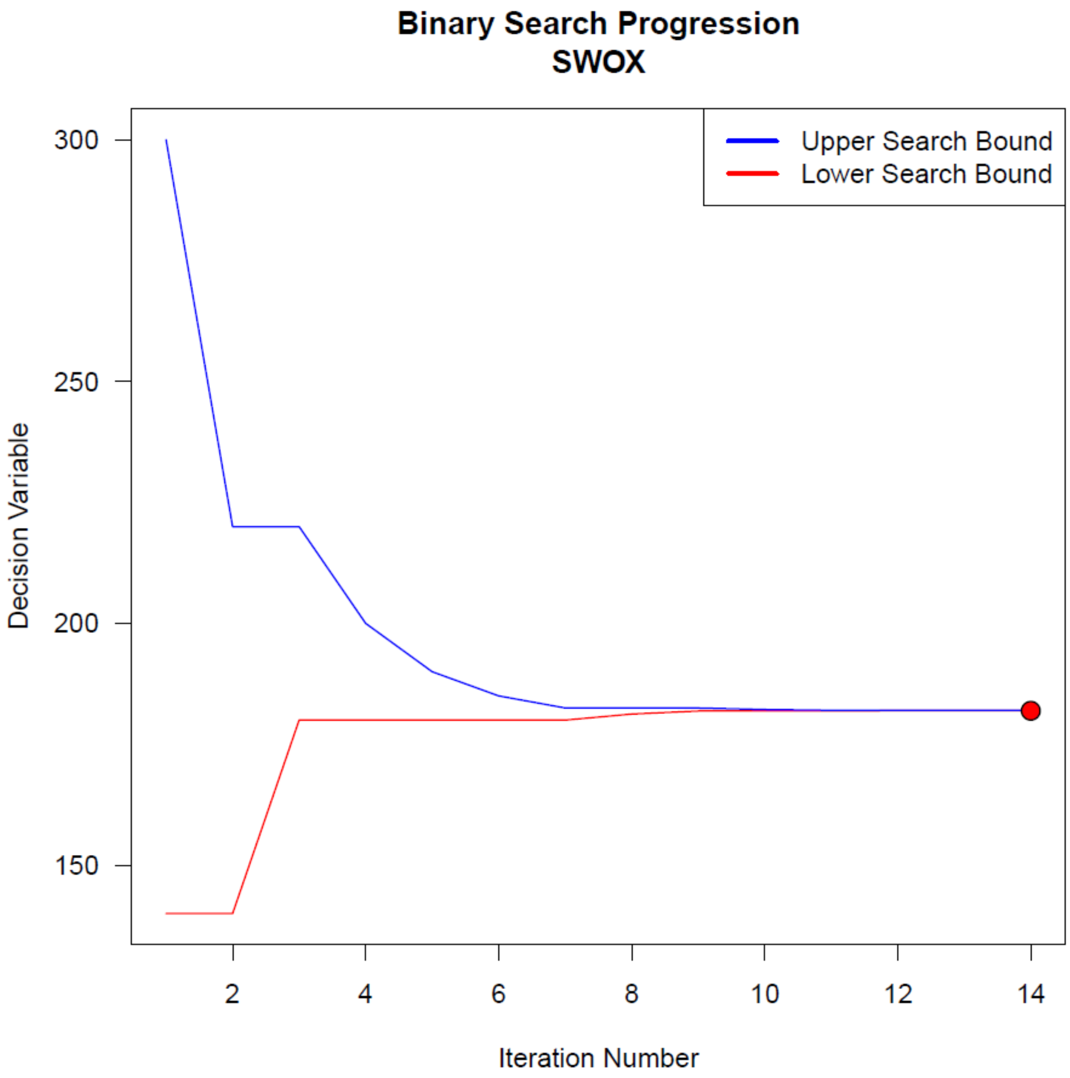


Figure B.1 Example of binary search for SWOX demand

B.2.2 Models with multiple demand nodes

For the case study models with more than one demand node (Carlisle, Forest and Stroud, Ruthamford South and Wimbleball) the demand nodes cannot be maximised using a binary search process as outlined in section B.2.1 because the demand nodes may not be independent. For example, if two demands are both drawing from the same source there may be a trade-off in terms of how much they may each take from this source which is dictated by the combination of other sources on which the demands rely.

A multi-objective optimisation routine (Deb et al. 2002) was used to maximise the demand taken across multiple demand nodes. This works by generating an initial population of 200 sets of demands and running the water supply model for each set. The demands sets which provide the most demand without the system failing are then used to generate a new population of 200 sets of demand using the principles of natural selection and survival of the fittest. After five generations of this process the best performing demand sets were then summed to provide a total system demand from which the maximum was taken.

An example of this process is shown for the Forest and Stroud case study in Figure B.2. The first generated population is plotted in yellow, with each subsequent generation plotted as a colour increment towards the fifth and final generated population in red. The best performing demands in each population are shown as large circles. As the number of generations increase (yellow to red) the large circles can be seen to converge on the diagonal line. The area of the plot to the top and right of this diagonal would result in a supply-demand deficit in the water supply system model. This demonstrates the trade-off between the demand nodes where they each have an individual maximum but in combination they cannot both attain this maximum value.

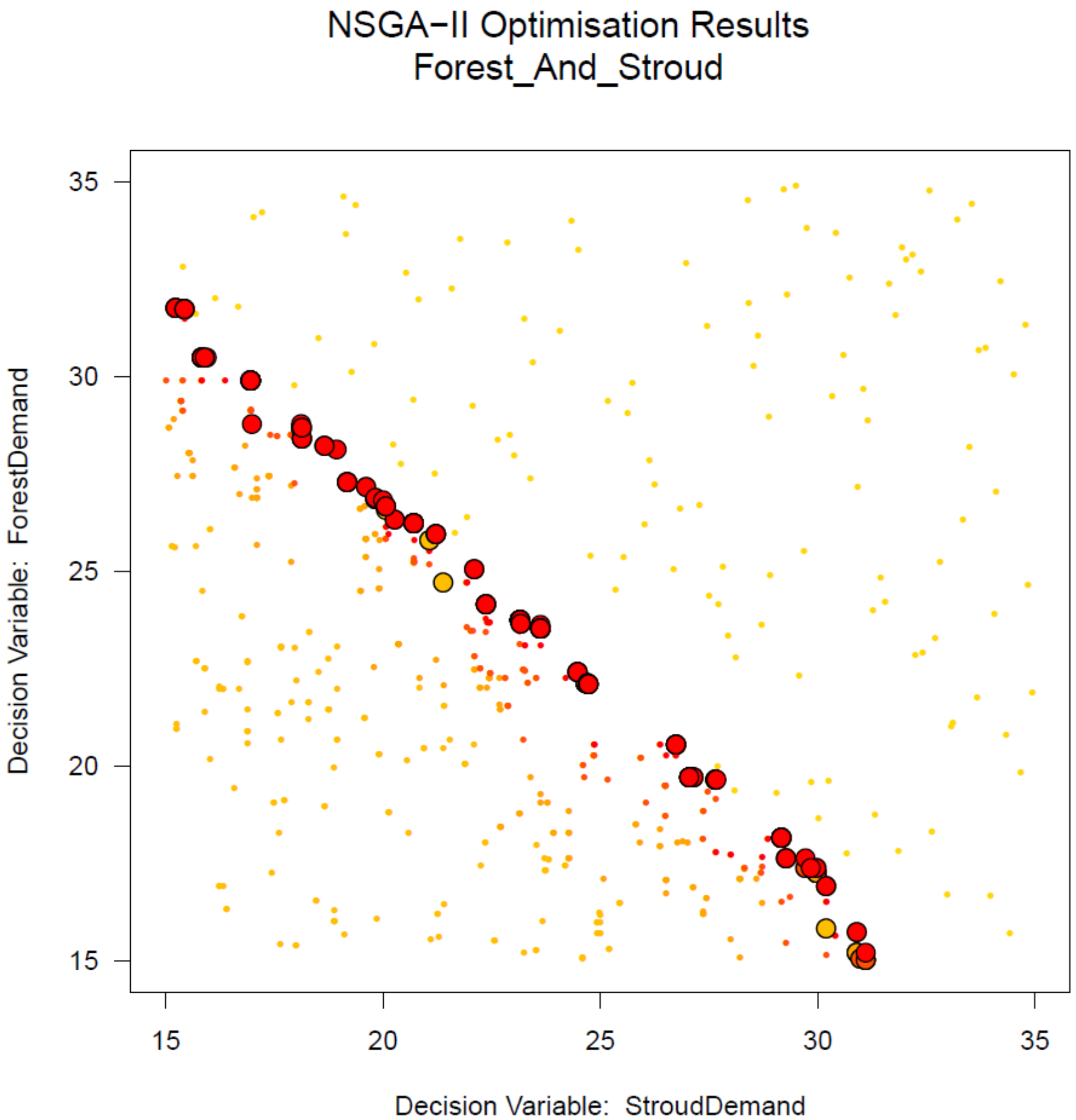


Figure B.2 Example of multi-objective optimisation for the Forest and Stroud case study

B.3 Standardisation results

The results of the demand standardisation are shown in Table B.1 and demonstrate how much the demand in each case study water supply system was changed in order to reach the point of failure in the historical period.

Table B.1 Comparison of pre- and post-optimisation demand

Case study	Original demand (Ml/day)	Optimised demand (Ml/day)	Optimisation increase (%)
Barmouth	1.41	2.48	76
Carlisle	28.51	37.35	31
Don Valley	80.40	95.73	19
Forest and Stroud	41.03	47.16	15
Hull	51.00	84.00	65
Ruthamford	273.20	309.40	13
Sussex North	66.00	65.00	-2
SWOX	141.90	182.00	28
Wimbleball	75.45	94.70	26

Table notes:
Optimised values of demand are not necessarily an accurate portrayal of the demand that can be supported from the real world system and are used here for comparative purposes only.

Appendix C: Methodology for calculation of varying rainfall deficits

Monthly intensity is defined for the time-variable ‘ProfWinter’ and ‘ProfSummer’ drought profiles as follows:

- annual absolute rainfall deficit corresponding to the drought intensity is calculated and expressed monthly
- monthly absolute deficit sequences are calculated from Eq. 1
- for each month, the monthly absolute deficit is removed from the corresponding monthly long-term average (in mm) and the corresponding deficit expressed as % monthly long-term average to create a drought intensity profile (bounded by 0)

$$\boldsymbol{X}(\boldsymbol{t}) = \boldsymbol{X}_{\boldsymbol{mean}} + \boldsymbol{A}\,\mathbf{cos}[\mathbf{2}\boldsymbol{\pi}(\boldsymbol{t} - \varphi)/\mathbf{12}] \qquad \text{(Eq. 1)}$$

where:

$X(t)$ monthly deficit in mm

X_{mean} mean annual deficit in mm

A harmonic amplitude (height of peak) equal to mean monthly absolute deficit divided by 2 in mm

φ harmonic phase (month of peak) equal to 1 for winter and 7 for summer profile

t month (1 for January to 12 for December)

Appendix D: Results for other metrics

D.1 Days with supply-demand deficit

The number of days with a supply-demand deficit as a metric is shown in Figure D.1. The metric is cumulative such that as the drought scenarios become longer in duration the number of days where a supply-demand deficit occurs will increase. The pattern of responses shown by the case studies is typically consistent with the proportion of unfulfilled demand metric used in the main report because the two metrics are closely correlated.

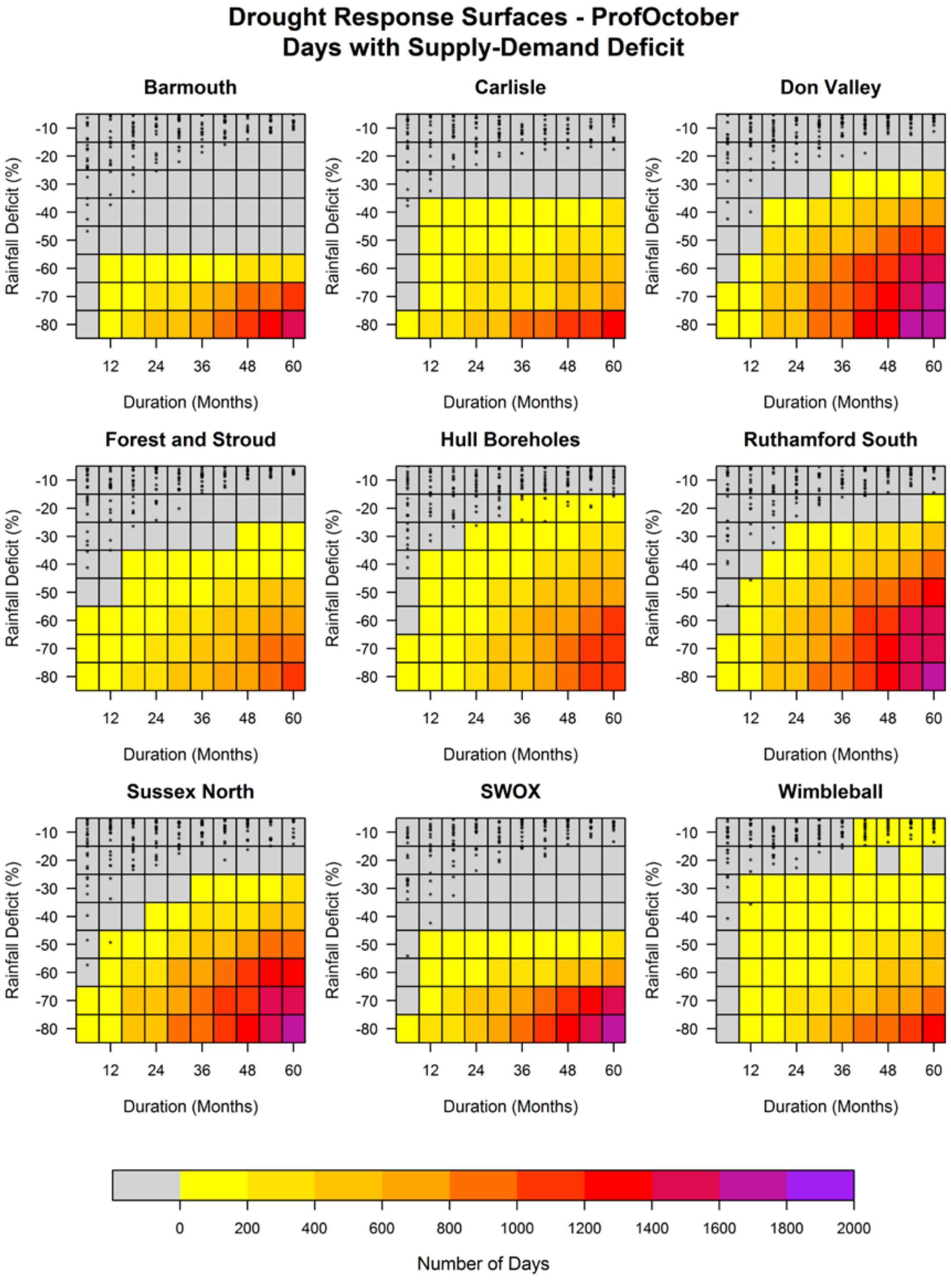


Figure D.1 Drought response surfaces for all case studies using a ProfOctober drought scenario for the number of days with supply-demand deficit metric

D.2 Proportion of scenario days with supply-demand deficit

Figure D.2 displays the proportion of scenario days with a supply-demand deficit as a percentage (that is 0–100%). The main factor controlling this metric is the severity of the drought scenario as opposed to drought duration. This is in part due to the duration element being standardised by calculating the number of supply-demand deficit days as a proportion of the drought scenario duration. However, in all case studies it can be observed that the shorter duration events (6–18 months) typically have a lower proportion of days with a supply-demand deficit as a result of the residual effects of the prevalence of long-term average conditions during the drought run-in period. A drought scenario of the same rainfall deficit but different duration undergoes the same first 6–18 months, meaning that once the drought is established it will then continue, resulting in a greater proportion of the supply-demand deficit days beyond 18 months.

A seasonality component can also be detected in the largest rainfall deficits in some case studies (Carlisle, Don Valley, Ruthamford South, Sussex North), where alternate scenario durations lead to fluctuations in the proportion of scenario days with a supply-demand deficit as the duration increases. This is caused by the characteristics of the drought termination. Where a deficit terminates at the start of spring the water supply system is naturally beginning its summer drawdown cycle meaning that supply-demand deficits may be possible depending on the resource state at the end of the drought scenario. Where the drought scenario ends in September the normal winter refill/recharge season supports the drought recovery phase minimising the risk of any further supply-demand deficits. These different characteristics result in the seasonal cycle that can be observed for the case studies previously mentioned.

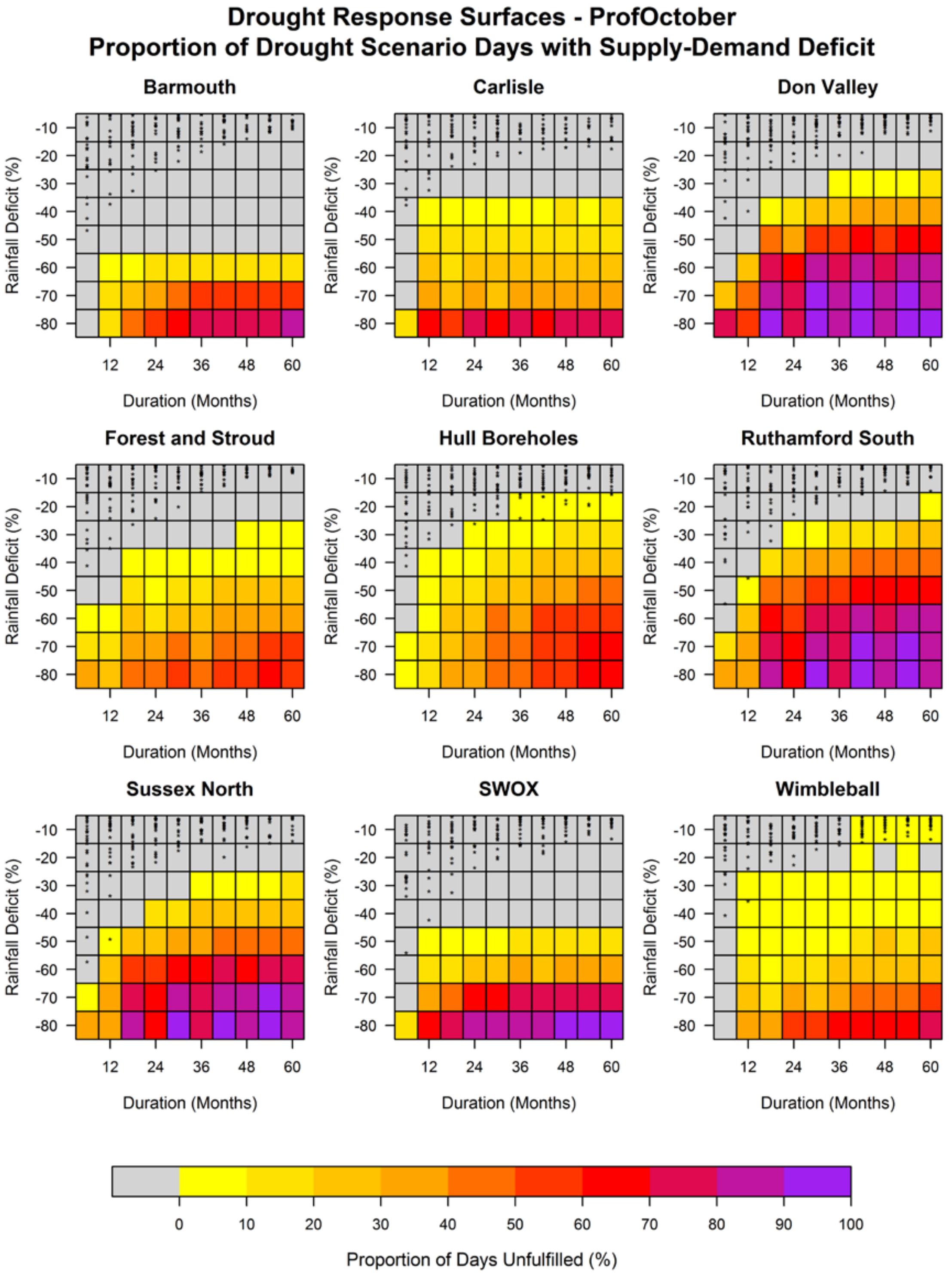


Figure D.2 Drought response surfaces for all case studies using a ProfOctober drought scenario for the proportion of scenario days with supply-demand deficit metric

D.3 Average proportion of unfulfilled demand per day

The average proportion of unfulfilled demand per day is presented in Figure D.3, and summarises the demand that cannot be met on days when a supply-demand deficit occurs. In its simplest interpretation this metric describes how much a system fails to meet the demand requested.

Barmouth and Don Valley display the highest proportion of unfulfilled demand, close to 100% during a period of supply-demand deficits, as a consequence of the modelled reservoir storage reaching zero and the relatively small inflows. The other reservoir-only case studies, Ruthamford South and SWOX, have a lower proportion (~60%) due to a larger available inflow from the River Ouse and Thames respectively.

Carlisle has a proportion of 50% whereby the reservoir component of the system fails but the large abstraction from the River Eden is maintained during even the most severe drought scenarios. Sussex North has a number of sources used conjunctively (run of river, groundwater, reservoir, transfers) meaning that the system typically has a lower proportion of unfulfilled demand, ~30%.

Forest and Stroud and Wimbleball both have the smallest proportion of unfulfilled demand (~10–20%). Both systems have a significant contribution of resilient groundwater sources coupled with a river abstraction which is regulated by an upstream reservoir. When a supply-demand deficit occurs it is typically a result of the day to day variability in river flows coupled with how much regulation volume can be provided to ‘top up’ the river flows, which results in only a very small unfulfilled demand.

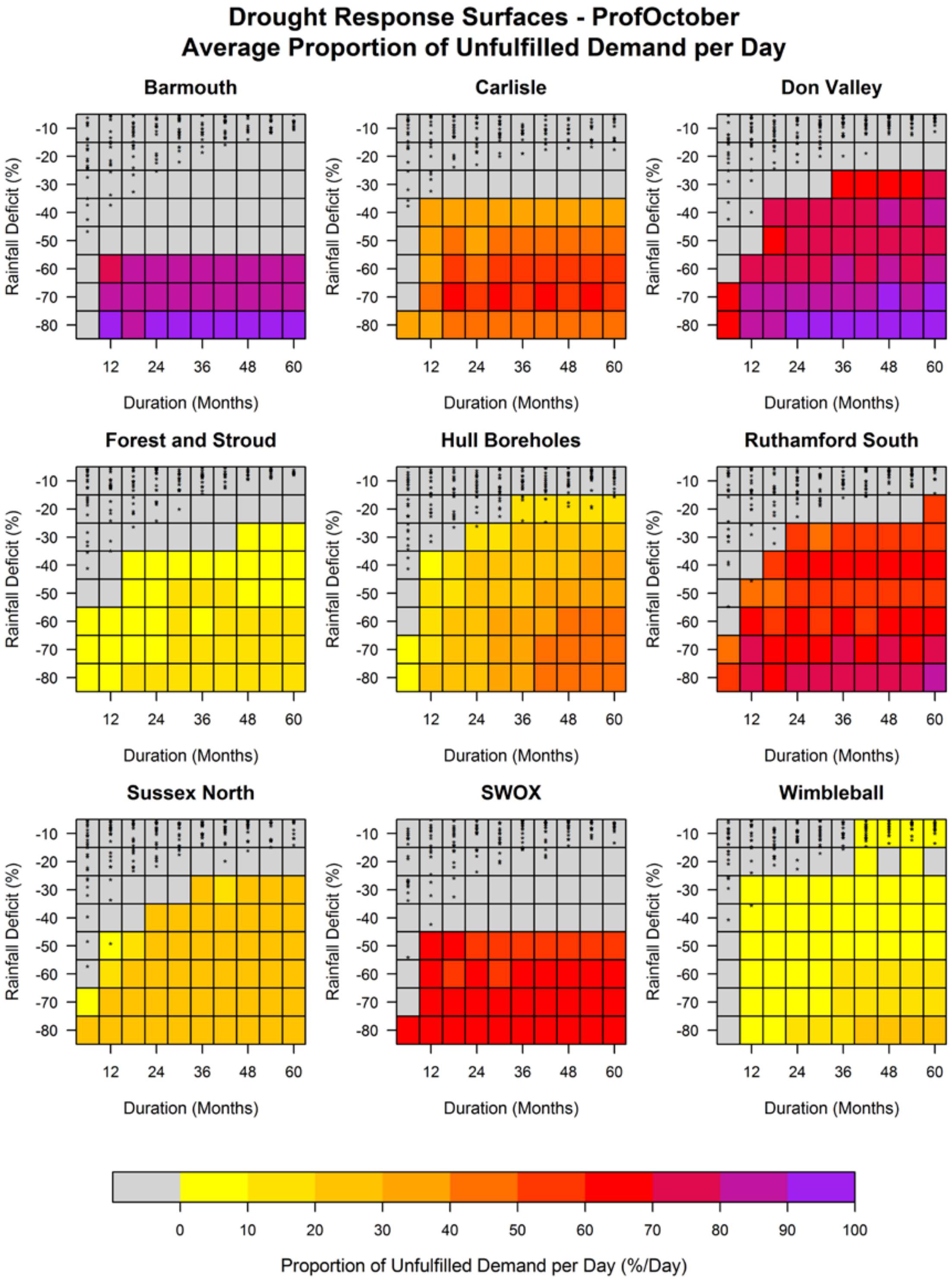


Figure D.3 Drought response surfaces for all case studies using a ProfOctober drought scenario for the average proportion of unfulfilled demand per day

D.4 Total unfulfilled demand

The total unfulfilled demand, presented in Figure D.4, is the cumulative total of the demand that cannot be met over the course of the drought scenario. This provides information on the absolute impact of a drought scenario as opposed to the relative impacts for a given case study which is shown by the other metrics.

Ruthamford South, SWOX and Don Valley can be seen to have the largest total unfulfilled demand. For Ruthamford South and SWOX, this result is consistent with the fact that they were the two largest supply systems tested, in terms of deployable output (as noted in Table 2.1). For Don Valley, this is an indication of the low resilience of this system when removed from the context of the Yorkshire Grid integrated resource zone, of which it forms a part. The remaining case studies are all much smaller relative to these three.

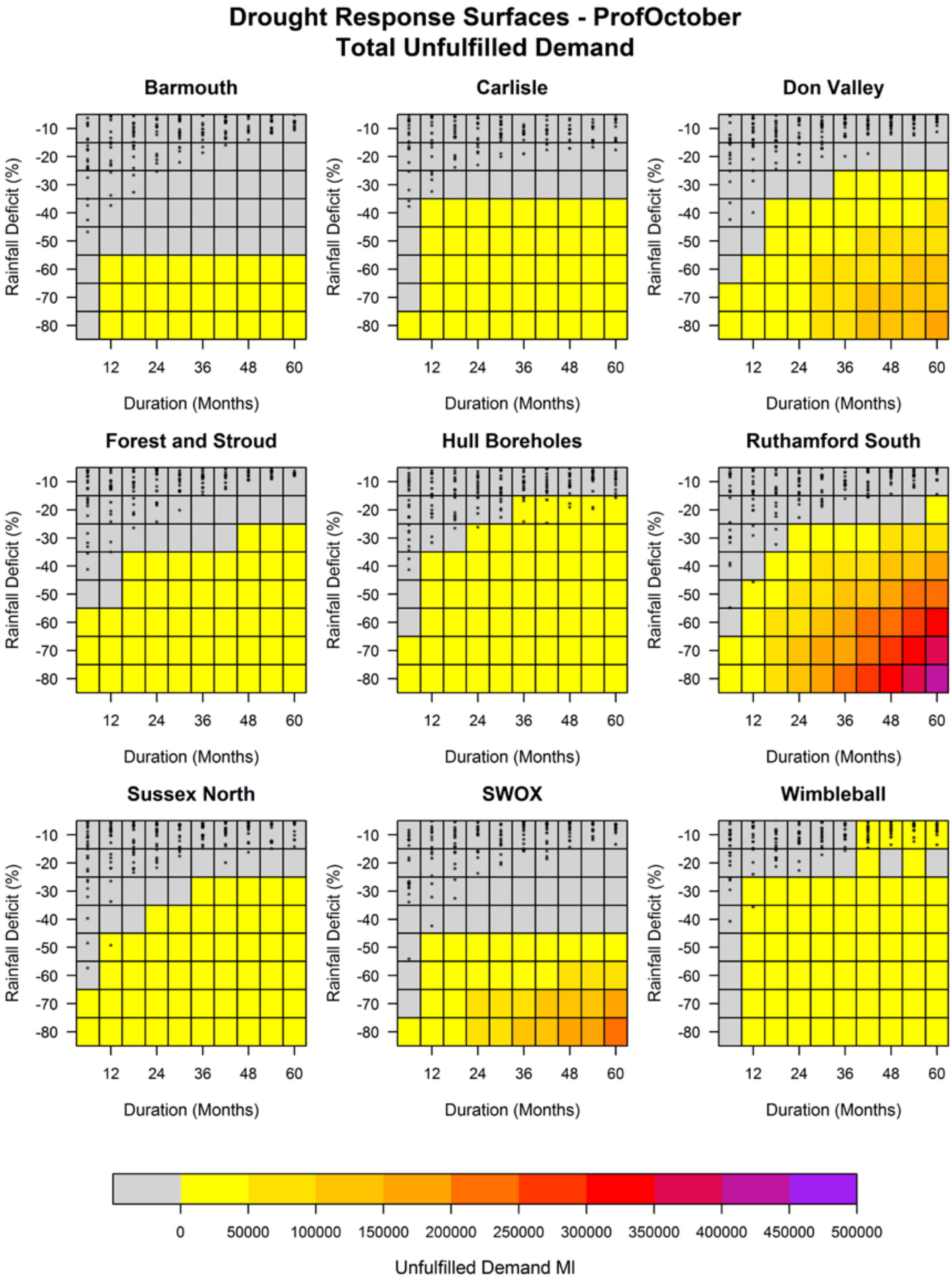


Figure D.4 Drought response surfaces for all case studies using a ProfOctober drought scenario for the total unfulfilled demand

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