Ref B2.20.WSH.CE.A1

Improving drought resilience in the Vowchurch water resources zone IAP response

1 April 2019

Contents

1. IAP challenge

Ofwat have rejected the enhancement expenditure for the Hereford to Vowchurch interconnection due to insufficient evidence provided for the need to invest.

Extracts from Ofwat's supply demand balance enhancement feeder model:

"The investment is driven by potential vulnerability to severe drought (return period at least 1 in 200 years). The company's WRMP appendix 19 describes considerable uncertainty associated with the Extreme Value Analysis used to justify this: "it is apparent that the risk of breaching the licenced abstraction allowance during a 1 in 200 year event is relatively limited and it is noted that the Vowchurch abstraction is actually taken from river gravels which are hydraulically linked to the river, so there may be some storage element that would reduce the impact on DO if this did occur. Further resilience testing using more advanced methods may therefore be justified in the future, but for WRMP19 it is concluded that the supply/demand balance is not affected for a 1 in 200 year event.

"Further to whether there is a robust need for investment, there is insufficient evidence to show that a transfer is the best option for customers, or that customers support the added resilience or the chosen option and its associated costs."

2. Summary of our response to the Initial Assessment by Ofwat

Ofwat consider that we had not presented sufficient evidence of the need for the drought resilience scheme in the Vowchurch zone.

In this document we present a full investment case for the scheme, to allow Ofwat to undertake a full 'deep dive' review of the case.

3. Introduction

Our September 2018 business plan submission allocated £6m for a new water main between our Hereford and Vowchurch water resource zones – *PR19 Ref 5.8A, Section 4, Preferred Option, p.26.* The scheme is driven by the need to provide resilience to at least a 1 in 200 year return period (0.5% annual probability) drought event in the Vowchurch zone.

Our WRMP19 was published in March 2019. It includes further information and clarifications relating to the Vowchurch zone drought vulnerability that were not available in September 2018. The relevant information is contained in:

- Final WRMP19 – Main Plan, Section 7.14
- Final WRMP19 - Appendix 19, Extreme Value Analysis, Section 3.14
- Drought Plan Technical Note – DCWW Drought Vulnerability Framework, Vowchurch Analysis and Response Surface (Appendix 1 to this document).

3.1. Summary of our response

The Vowchurch zone has a positive supply demand balance but we have undertaken two types of drought analysis – extreme value analysis and drought response surface analysis. These have indicated that in a 1 in 200 year drought event there would be insufficient flow in the river to supply the demand in the zone. This means we are unable to meet our performance commitment (Ft1), to have no properties at risk of severe restrictions in a drought without undertaking investment in the zone.

We have considered a range of options including transfer from an adjacent water company, additional water storage in the zone, demand reduction measures and transfer from an alternative source within our own network. Full cost-benefit analysis was undertaken on these options and the preferred option was selected to construct a transfer from our Broomy Hill water treatment works in Hereford. The value of this scheme is £5.83m (post efficiency challenge).

Owing to the further information now available, we are able to provide further evidence to Ofwat, and invite Ofwat to reconsider their assessment of this case. We believe that there is a clear need, and that the scheme chosen from the options available provides good value for customers.

Further details are provided in the following sections.

4. Need for investment

4.1. Water Resources Management Plan

The Vowchurch water resource zone covers the small rural area south of Hay-on-Wye, (Figure 1).

The zone is supplied by three operational boreholes that are located adjacent to the River Dore in the village of Vowchurch. The River Dore is a tributary of the Monnow that, in turn, is a tributary of the River Wye.

There are small distribution network links from the Hereford and Llyswen zones which can provide 0.46 and 0.13Ml/d respectively, supporting customer water needs during peak demand periods. There are no exports of water.

Figure 1 - Vowchurch WRZ

WRZ No.	WRZ Name	Area (km2)	Population served ('000)	Distribution Input (Ml/d)	Main Source of Water
8110	Vowchurch	250	6.7	2.2	Groundwater abstraction

The Deployable Output (DO) for the zone under the “Dry Year Annual Average” AADO scenario is 2.36Ml/d and “Dry Year Critical Period” CPDO 3.0Ml/d, constrained by environmental needs through abstraction licence limits.

The zonal level of service regarding Temporary Use Bans is >1:43 (TUB - target not more than 1 in 20 years) and Non-Essential Use Bans >1:43 (NEUB – target not more than 1 in 40 years). Our previous level of service against extreme supply side measures was “Never” but given government and our own concerns over the resilience of our water resource position we have moved to a new enhanced measure of resilience to droughts that might occur every 1 in 200 years (a 0.5% risk).

4.2. Understanding the level of risk in relation to drought

As laid out in our WRMP19 and our forthcoming Drought Plan, to understand the level of resilience in each zone we have used new innovative statistical methods in line with the recent Drought Vulnerability Framework approved by Welsh Government. This examines whether our supply systems could cope with droughts of various severities/frequencies. We have undertaken two studies, using different methodologies, to verify our understanding of the level of risk. The studies can be made available if required. Results from the two studies confirm that this zone is not currently resilient to a 1 in 200 year return period (or 0.5% probability) event.

4.3. Extreme Value Analysis

Appendix 19 of the WRMP19 contains the report: Welsh Water Extreme Value Analysis, Evaluating the resilience of WRZs to extreme drought events, Atkins, August 2018.

This initial resilience assessment indicated that the River Dore and associated gravel aquifer may not provide the required yield to meet customer demands under drought events more extreme than we have seen historically, such as those experienced in 1976, 1984, 1989/90 and 1995. The analysis showed that in a 1 in 200 year drought event, the boreholes and the associated River Dore may only provide 0.83 Ml/d, compared to our abstraction needs of up to 3 Ml/d. This was based on our knowledge of the aquifer from which the Vowchurch boreholes abstract water and the currently available River Dore flow record, where relatively low flows have been experienced.

We commissioned our Drought Vulnerability Framework project to improve confidence in this initial assessment.

4.4. Drought Vulnerability Framework

Since September 2018 we have an improved understanding of the drought risk for the Vowchurch zone, made possible by the analysis of a longer stochastic flow record for the River Dore. The work is reported in: *Technical Note, DCWW Drought Vulnerability Framework, Vowchurch Analysis and Response Surface, Atkins, December 2018.* This note will be issued as an Appendix to our Draft Drought Plan, submitted to Welsh Government at the end of March.

For the Vowchurch groundwater abstraction the sustainability of the source during drought events is dependent on the availability of recharge flow from the nearby river. If the flow in the river falls below the required abstraction rate then it is likely that the aquifer will begin to dewater, with the associated risk of complete source failure from the shallow boreholes. Although the exact relationship between this event and aquifer drawdown is unknown, the duration when river flows will be below customer demand (and hence the need to abstract at this rate) is a measure of the drought risk faced by the source.

Our analysis uses the historical river flow record and rainfall to stochastically generate a long term flow sequence, both with and without 2030s climate change. Of most concern are the droughts ending in August or September, when we have low groundwater levels and low flows.

The analysis has been used to plot a drought response surface for the zone (Figures 2 and 3 below). The zonal 'failure' is represented as the estimated duration where flows in the River Dore at the abstraction site will fall below demand. The key findings of the analysis are:

- The baseline (no climate change) drought risk analysis indicates that during a 1 in 50 year type of event it would be expected that flows could fall below the zonal demand for up to a week in the year. Although difficult in this rural area, with relatively low demand shortfall, we would manage this risk through tankering. In a 1 in 200 year event this duration increases to the order of a month and with greater deficit against borehole yield. This would be at a time when tankering availability would be very low and is a very high risk position for public water supply.
- Under 2030s climate change assumptions, the expected duration where flows would be less than abstraction during a 1 in 50 year event increases to around a month. For a 1 in 200 year event the expected duration could be several months.

- The key conclusion that can be drawn from the analysis is that significant risks will occur during rainfall deficit events of around 1 in 100 or more, but these can develop quickly, for durations of 6 months or less. The risk is similar for the period ending August and September – i.e. such events will tend to happen during dry periods that extend into the late summer.

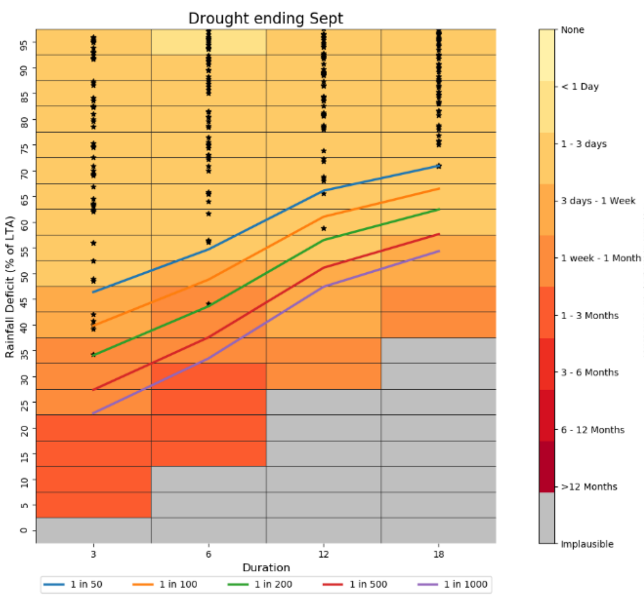

Figure 2- Vowchurch Drought Response Surface, No CC

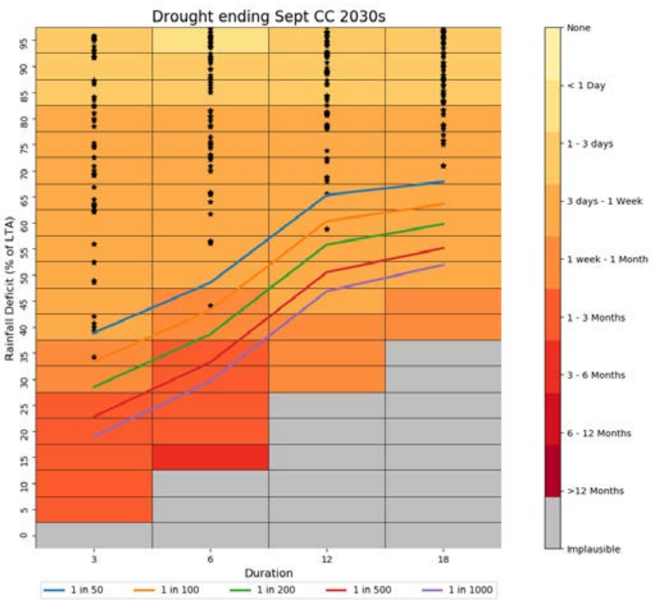

Figure 3 - Vowchurch Drought Response Surface with CC

4.5. Customer engagement

We have sought our customers' views regarding the level of water resource service that they would prefer across our region. We are already meeting or exceeding this in the majority of our WRZs, for the frequency with which we would need to restrict demand through the use of hosepipe or non-essential use bans. However, our customers' preferences suggest that we should look to improve our level of resilience against severe drought – more severe than a 1 in 100 year return period.

Our WRMP Research, Final Report, December 2017 states:

"Results from our analysis of the exercise found that many DCWW customers attached a high value to the improvement in resilience from 1 in 100 to 1 in 200. We calculated a lower bound estimate of mean WTP for the improvement option of 5.4% of households' current bills, on average, in real terms, and 5.1% of non-households' current bills. This equates to £23.70 per household per year for households and £96.80 per year, on average, for non-households."

At these rates, and with our household and non-household numbers, the annual willingness to pay amounts to ~£43m. This comfortably exceeds our proposed AMP7 total capital expenditure on supply-side enhancement schemes of £26.69m, which includes £5.83m for the Vowchurch scheme.

5. Optioneering

5.1. Temporary mitigation

We have considered the availability of mitigation options in the event of low flows in the river.

Tankering from another WRZ, e.g. Hereford, could provide some mitigation for short periods but this is not a practical solution for drought events lasting more than a month, as projected. Our potable water tankers are capable of carrying 30,000 litres each. Delivering 2 to 3 Ml/d would require 67 to 100 tanker loads per day, which would be unsustainable in a 1 in 200 year drought scenario. In other words, we would not be able to avoid imposing *more extreme measures such as significant pressure management, or even more restrictive practices,* as set out in our WRMP defined Level of Service. We have stated that this is unacceptable, thus confirming the need to provide a permanent solution.

5.2. Water trading options

Importing water from another company is not a practical mitigation option. The nearest neighbouring company, Severn Trent, is further away than our major abstraction source on the River Wye at Broomy Hill. Given that the Broomy Hill source has sufficient supply in the 1 in 200 year drought scenario to feed Vowchurch, the costs involved in constructing the required pipeline would be greater than our proposed solution.

5.3. Engineering options

The Vowchurch site has been subject to environmental investigations by the Environment Agency which confirmed that the current abstraction licence is at its limit of sustainability.

Given that we cannot increase abstraction, three further resilience options have been considered:

- Option 1 – reduce leakage in the distribution system
- Option 2 – construct storage adjacent to the boreholes
- Option 3 – lay a new transfer main from Hereford WRZ.

These options were first developed and assessed as part of a Restoring Sustainable Abstraction (RSA) study in 2010/11 as required by the Environment Agency through the National Environment Programme for AMP 5 – *River Dore and tributaries RSA analysis Phase 1: Cost-benefit analysis, Scott Wilson, November 2010.*

5.4. Option 1 – Reduce leakage

A range of alternative leakage schemes were appraised for the draft WRMP19. The measures, costs and potential leakage savings are given below:

Scheme category	**Cost range £m/Mld**	**Cumulative saving (within each category) Ml/d**
Renewal of Mains, Comms & Customer Supply Pipes (CSP)	28 - 78	0.503
Renewal of Comms & CSP	9 - 16	0.286
Renewal of Mains & Comms	36 - 93	0.423
Pressure Management schemes	1	0.054
Policy Minimum Leakage Detection	2 - 7	0.024
Smart Metering	10 - 12	0.121
Trunk Main renewal schemes	145 – 32,097	0.007
Trunk Main repair schemes	20 – 30,304	0.005

Only two of these categories have scheme costs less than £9m per Ml/d and the combined saving from all schemes in these two categories amounts to less than 0.08 Ml/d. With the deficit at approximately 2.2 Ml/d, it can be seen that: (a) leakage measures alone would be insufficient to meet this requirement, and; (b) the costs in attempting to achieve maximum leakage savings would rapidly become highly inefficient. For example, delivering the most cost effective schemes first, the cost would exceed £20m before even a cumulative saving of 0.75 Ml/d were achieved.

5.5. Option 2 – Bank-side storage

This option would allow us to store water near to the boreholes or Water Treatment Works, then abstract it from the storage reservoir and feed it directly into supply. The costs were estimated as follows:

Element	**£m**
Capital Costs	12.7
Annual Operating and Maintenance Costs	0.8
Present Value (25yr, 3.5% discount rate)	16.0

The costs for a 30 Ml storage reservoir are shown in the table above, but given the level of shortfall predicted under a 1:200 drought event, a significantly higher storage volume would be required, with associated higher cost.

5.6. Option 3 – Transfer main from Broomy Hill, Hereford WRZ.

This option comprises an upgrade to Broomy Hill Water Pumping Station, approximately 14km of new mains (up to 280mm diameter) and a crossing of the River Wye. This will permit the transfer of 3Ml/d from Broomy Hill in Hereford WRZ into Vowchurch WRZ via two existing Service Reservoirs at Aconbury and Kingstone.

The costs were estimated as follows:

Element	£m
Capital Costs[1]	4.9
Annual Operating and Maintenance Costs	0.7
Present Value (25yr, 3.5% discount rate)	5.8

A new potable water main between our Hereford and Vowchurch zones would be capable of meeting the whole Vowchurch demand from Broomy Hill WTW when needed. Broomy Hill is fed by abstraction from the River Wye and is licensed for a maximum rate of 52 Ml/d. The resilience assessment of this river source suggests there is no plausible drought severe enough to deplete flows in the River Wye to such an extent that they would be unable to provide 52 Ml/d for abstraction at Broomy Hill. We are therefore confident that this new supply of water to Vowchurch is fully drought resilient.

[N.B. the RSA report identified a total of six transfer options, ranging from 0.5Ml/d to 3 Ml/d. Of these, the option included here was preferred because it had the highest Net Present Value (PV benefits minus PV costs). This option also had a lower cost than the only other option capable of providing 3 Ml/d.]

5.7. Options Assessment

The latest drought risk analysis has confirmed the need for a permanent solution (rather than tankering) to provide 1 in 200 year resilience. Leakage reduction (Option 1) cannot come close to meeting the deficit – for example, delivering the most cost effective schemes first, the cost would exceed £20m before even a cumulative saving of 0.75 Ml/d were achieved. Bankside storage (Option 2) is more than double the cost of a new transfer main (Option 3) and, based on the findings of our latest analysis, would still not provide sufficient drought resilience unless it were significantly larger.

A new transfer from Broomy Hill, Hereford WRZ into Vowchurch (Option 3) remains as the clear preferred solution. Additional arguments for this option are given in the following sections.

In addition to capital and operating costs, the RSA report included a thorough assessment of environmental and social costs, and benefits.

The results are summarised as follows:

[1] For options comparison purposes, this is the capital cost in the RSA report. This was in 2009/10 prices and excluded any pre-construction costs such as feasibility or design. The updated scheme capex for PR19, as submitted at Sep 2018, is £5.83m.

	Option 1 – Reduced leakage (0.33 Ml/d into supply)	**Option 2** – Bankside storage (0.8 Ml/d into supply from storage reservoir)	**Option 3** – Transfer main (3 Ml/d into supply from Broomy Hill, Hereford WRZ)
NPV (Net Present Value - PV of benefits minus PV of costs)	-£1.54m	-£13.07m	£5.54m
BCR (Benefit-cost ratio)	0.45	0.19	1.91

The transfer option is the only one in which the present value of benefits exceeds the present value of costs, and its benefit-cost ratio is the highest by a significant margin.

5.8. Environmental benefit

The benefits in the analysis reported above are associated with recreation, angling and conservation value/biodiversity. However, the last of these, the environmental benefit, makes up 96% of the total benefit value, so is by far the most significant element.

The RSA report states: *"While the river does not have any special, protected status and is not included in the River Wye SAC (Special Area of Conservation) designation, the EA raised concerns about the impact of the Vowchurch abstractions on fisheries (particularly upstream fish migration), aquatic macrophytes (specifically Ranunculus), water voles, native crayfish and other species that utilise the River Dore as a wildlife corridor.*

Reducing the level of abstractions, or at least ensuring that benchmark flows are not compromised, is expected to result in an improvement (or at least maintenance) in the ecological quality of the river, including provision of habitats for protected and other valued species."

In the period since this report, the Vowchurch site has been subject to environmental investigations and we aware that the current abstraction licence is viewed at its limit of sustainability by the EA. Our proposed transfer main will ensure that we have a limited impact on the site under severe drought conditions and the EA supports this.

6. Preferred option

The preferred option is a new transfer from Broomy Hill, Hereford. Scheme elements and costs are as follows:

Scheme element	Cost (£m)
New Water Pumping Station (3Ml/d, 40 l/s) and kiosk at Broomy Hill, with SCADA facilities to measure flow and quality.	0.50
New 280mm HPPE trunk main from Aconbury Service Reservoir (1.7km in highway, 0.6km in verge)	0.88
New 250mm HPPE trunk main to Kingstone Service Reservoir (4.5km in highway)	1.61
New 280mm HPPE trunk main from Kingstone Service Reservoir to Vowchurch supply area (7.25km in highway)	2.84
Total	**5.83**

1. SCADA – Supervisory control and data acquisition
2. HPPE – High performance polyethylene
3. Costs are from our Unit Cost Database, 17/18 price base and post-efficiency.

The new 250mm HPPE main to Kingstone SR will run alongside an existing 180mm MDPE distribution main. The new 280mm HPPE main from Kingstone SR will be dedicated to bring the required 3 Ml/d into the Vowchurch supply area; the existing distribution mains in this area are not big enough for this purpose.

6.1. Customer protection

We have included a performance commitment within our plan to ensure that we deliver increased drought resilience (Ft1). This has a reputational outcome delivery incentive.

7. Conclusions

The conclusions from this investment case are:

- Resilience to the 1 in 200 year drought event, e.g. not having to impose *'extreme measures such significant pressure management or more restrictive practices'* is part of the stated Level of Service in our WRMP19.
- Our drought vulnerability framework studies have demonstrated that the supply available at the Vowchurch source could fall below the required demand for periods 'longer than a month' during 1:200 year drought conditions.
- The duration of this deficit period is such that mitigation options such as tankering would not be a practical means of providing the required resilience, hence the confirmed need for a permanent solution.
- We assessed alternative options - leakage reduction, bankside storage, and a new transfer main. Both leakage reduction and bankside storage options become significantly more expensive than a transfer main before even reaching the required supply rate.
- The transfer main option has the highest reward (present value benefits minus present value costs) and highest benefit cost ratio.
- The environmental benefits (conservation and biodiversity) are significantly higher for the transfer option. The EA considers our current abstraction to be at its limit and supports the prospect of an alternative supply from the River Wye so as to protect the much smaller River Dore in drought conditions.
- Our customer research has demonstrated a Willingness to Pay (WtP) value, i.e. for providing > 1:100 drought resilience, well in excess of that required to fund our proposal.

Appendix 1 Technical Note, DCWW Drought Vulnerability Framework, Vowchurch Analysis and Response Surface, Atkins, December 2018

Drought Vulnerability Framework

Final Project Report

Welsh Water

22 March 2019

Notice

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Document history

Revision	Purpose description	Origin-ated	Checked	Reviewed	Author-ised	Date
Rev 1.0	Draft for review	DH LP NU	SA	SA	BC	19/03/2019
Rev 2.0	Final report	DH LP NU	SA	SA	BC	22/03/2019

Contents

Tables

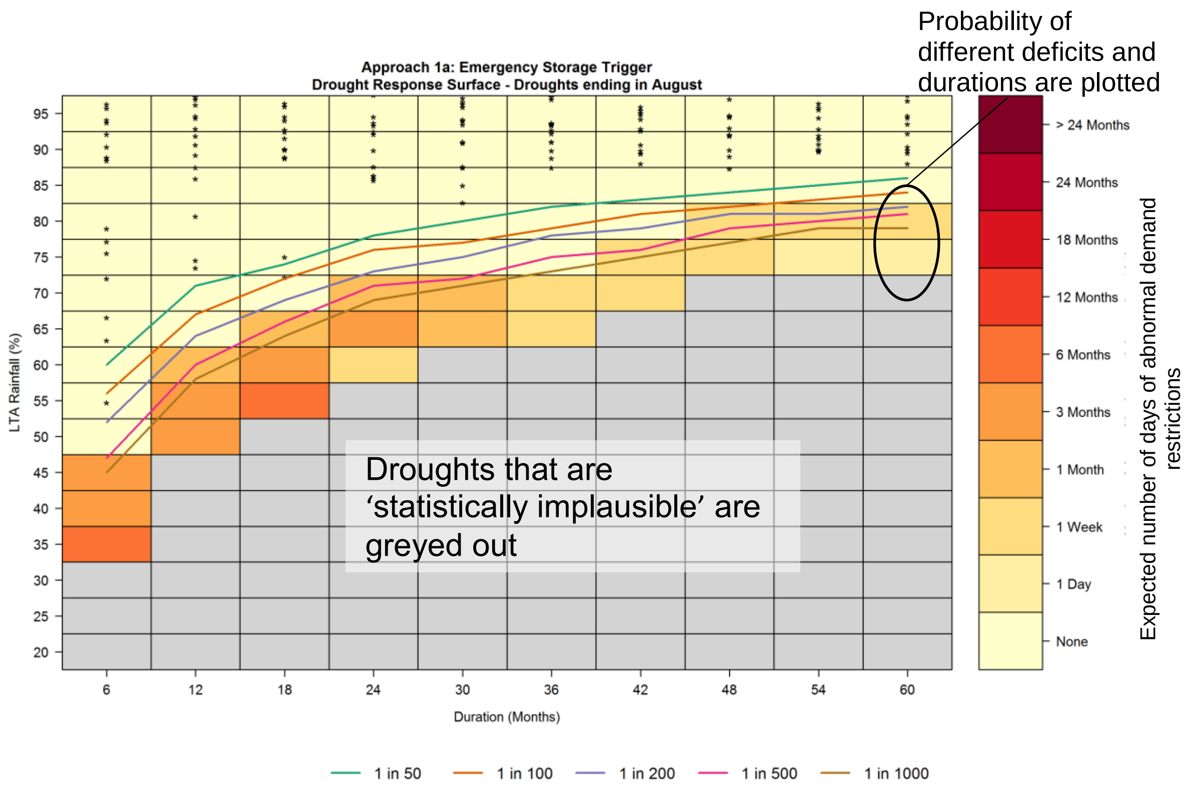
Figures

1. Introduction

As part of the Drought Plan 2020 preparation, Dŵr Cymru Welsh Water (DCWW) commissioned Atkins to carry out a drought vulnerability assessment for each of its Water Resource Zones (WRZs), in accordance with the Drought Vulnerability Framework (DVF) guidance that was jointly published by Natural Resources Wales (NRW) and the Environment Agency (EA) in 2017.

The concepts and format of the DVF are fully described in the 2017 guidance report, but in summary it is an evaluation process that seeks to identify the level of drought risk that is faced by a WRZ across a range of droughts of varying durations and severities, as characterised by rainfall deficits. The drought risk is quantified by calculating the number of days of supply/demand 'failure' that are expected to occur for each scenario. In this case, each 'scenario' represents a specific combination of duration and percentage deficit that occurs prior to a defined critical month for the drought (e.g. a 40% rainfall deficit experienced over a period of 12 months ending in September). The deficits for each scenario are plotted on a Drought Response Surface (DRS), along with curves that indicate the likelihood (based on return period analysis) that each deficit will be experienced. An example output DRS, along with the 'core concept' note contained in the DVF report, is replicated in Figure 1-1 below.

In some WRZs, it was possible to establish there is no risk of failure from statistically plausible droughts without the need to undertake a full assessment, or produce a DRS. Furthermore, where a DRS was required there are different approaches that could be taken depending on: (i) the degree of drought risk; (ii) data / model availability; and (iii) the characteristics of the WRZ. Section 2 therefore outlines the screening used to identify those WRZs that required a full vulnerability assessment, and the selection of an appropriate framework method. Section 3 describes in detail the approach used to generate the DRS for each shortlisted WRZ (including a baseline and climate change impacted DRS). The full details and results of the assessment for each WRZ are provided in Section 4, and the conclusions in Section 5.



The core concept behind the DRS is that it shows what sort of duration and timing is most critical to a given WRZ. Obviously any system will be more affected by a given level of rainfall deficit the longer that deficit goes on for. However, on the other hand the *probability* that the given level of deficit will occur reduces as the duration increases.

The DRS therefore shows the level of resource stress (as indicated by a 'number of days' failure' metric) that occurs in each deficit/duration cell of the matrix, *and* indicates the probability that a given combination of deficit and duration would occur (including where combinations are statistically implausible given the historically available data). Statistically 'implausible' drought events are greyed out on the response surface.

Figure 1-1 - Example DRS and DVF Concept Note

2. Screening and method selection

2.1. Rationale and Approach

The majority of WRZs within the DCWW supply area are forecast to have a healthy supply/demand surplus throughout the planning period 2020 to 2050. Alongside this, the initial analysis carried out for the WRMP19 resilience assessment project[1] demonstrated that there are a number of WRZs where there is no risk of shortfalls in supply occurring under any statistically plausible drought event. The initial draft versions of the DVF manual contained some general guidance on when and why WRZs might be excluded from a full analysis, and it was considered appropriate to exclude such WRZs from the full DRS analysis provided it was clear on any reasonable basis that there is no plausible drought risk. The final version of the DVF recommends that exclusions are discussed with Natural Resources Wales (NRW).

Based on this, an initial screening process was applied to all DCWW WRZs for presentation to NRW. The exclusions were based on the following two criteria:

- For WRZs where the DO varies according to drought severity (i.e. they are hydrologically vulnerable), the supply/demand surplus was taken from the WRMP19 and compared against the Target Headroom. If actual headroom is more than twice Target Headroom, then the WRMP19 resilience analysis report was reviewed to determine the level of estimated risk for that WRZ. If this was found to be low then the WRZ was excluded from requiring a full DRS assessment, unless specific concerns were raised by DCWW. This stage of exclusion reflects the original process that was proposed in the DVF document, although it was later removed at the request of the EA.
- For WRZs where the sources are not logically drought vulnerable, then these were excluded provided there were no significant unknowns or concerns about the nature of those resources.

In some cases, WRZs were provisionally excluded pending further checks on specific aspects of certain sources.

For WRZs that were carried through the screening process and a DRS was required, then the choice of methodology was based on the level of risk that was apparent from the screening analysis, and the practical constraints that exist due to the availability of hydrological models. Many of the WRZs do not currently have any hydrological models and so testing carried out for the WRMP19 resilience report demonstrated that direct stochastic flow generation is a viable approach for those WRZs. Therefore, this did not necessarily represent a constraint on the complexity and quality of the analysis, but it did mean that droughts of given flow probabilities needed to be back translated to estimate the percentage rainfall deficits that were likely to lead to such conditions before the DRS could be completed.

Where risks were potentially high, then the WRZ was assigned a method 1a or 1b approach, with associated stochastic rainfall and/or flow generation. For other WRZs, these were assigned methods 3 or 4, depending on the availability of hydrological/hydrogeological models.

The results of this screening and methodology assignment process are provided in Section 2.2 below. Many of DCWW's WRZs contain surface water storage and hence required behavioural analysis modelling to allow the risk of deficit day to be evaluated for a given drought. Currently DCWW utilises the WRAPSim software which is not set up to run very large synthetic data sets through the behavioural models. A system of 'drought library' analysis was therefore required for the DRS development. Guidelines on the proposed approaches that were used for the development of drought libraries are provided in Section 3.1.1 of this report.

2.2. WRZ Classification Outcomes from the Screening and Selection Process

The screening and selection of methods is provided in Table 2-1 below. WRZs that were screened out of the analysis at the first stage are colour coded in green, and WRZs where a full DRS assessment was required are colour coded in red. WRZs where there was some risk, but it was

[1] Welsh Water WRMP19 Problem Characterisation Report, Atkins 2016

limited and hence a simpler DRS development method was required, are coloured in yellow. In a few cases it was considered likely that the WRZ should be screened out, but there are specific details that needed to be checked with DCWW staff. These have been coded in pale yellow and the conclusions added in bold type.

Table 2-1 - Summary of the Screening and Methodology Selection Results

WRZ	Outcome of Screening	Framework Method Proposed	Comments
Tywyn Aberdyfi	Full assessment required	Use stochastically generated flow sequences – method 1a	Higher risk WRZ with deficit at peak prior to the implementation of the WRMP19 scheme. Direct stochastic flow generation has been previously carried out. The deficit analysis can be run without using WRAPSim, so the full stochastic sequence can be run. Need to develop rainfall/flow relationships to assign deficits to the DRS.
Vowchurch	Full assessment required	Full stochastics – method 1a (using direct flow generation)	The WRMP19 resilience testing indicated there are large uncertainties, primarily because the biggest risk occurs during rare events such as 2003 when dry periods extend into September/October. Direct flow generation using stochastics is therefore proposed.
NEYM	Full assessment required	Full stochastics – method 1b	Although available headroom is generally more than twice Target Headroom, there are concerns about the relative resilience of mainland reservoirs versus Anglesey reservoirs, and some climate change vulnerability. The system complexity means stochastically based analyses are required. Need to generate drought libraries to ensure WRAPSim runs are manageable.
SEWCUS	Full assessment required	Use stochastically generated flow sequences – method 1b	Higher risk WRZ with a small surplus. Because direct flow generation has been used, it will be necessary to develop rainfall/inflow relationships (as outlined in the DVF)
Pembroke-shire	Full assessment required	Full stochastics – method 1b	Higher risk WRZ with initial deficit prior to the implementation of the WRMP19 scheme. Stochastic rainfall and flows already generated for WRMP19. Need to generate drought libraries to ensure WRAPSim runs are manageable.
Barmouth	Full assessment required	Stochastic rainfall and runoff generating a drought library to run through WRAPSim – method 1b	Available headroom is set to equal Target Headroom based on DCWW's ability to bring in additional supplies from neighbouring zones. However, some risk was indicated in the resilience testing, and there were some concerns raised during the 2018 summer dry weather event. Need to generate drought libraries to ensure WRAPSim runs are manageable. Rainfall and PET generation to be spatially consistent with Lleyn Harlech.

Lleyn Harlech	Full assessment required	Stochastic rainfall and runoff generating a drought library to run through WRAPSim – method 1b	Although headroom is more than three times Target Headroom, some risk was indicated in the resilience testing, and there were some concerns raised during the 2018 summer dry weather event. Need to generate drought libraries to ensure WRAPSim runs are manageable. **Updated position: drought resilience was subsequently tested in DCWW's new combined Barmouth-Lleyn Harlech WRZ Aquator model. This showed a high level of drought resilience, and removed the need to generate a DRS (Section 4.6)**
Tywi CUS	Possible risk at high return periods, so an assessment is needed	Hydrological models are available, but the system is relatively low risk, so method 3a proposed.	The risk is fairly marginal, with possible failures at return periods > 1 in 500 when demand is equal to DO. Available headroom is over three times Target Headroom throughout the WRMP19 planning period. A simpler method is therefore appropriate.
Clwyd Coastal	Risk low, but needed to be checked, so DRS assessment was required	Flow perturbation using rainfall/inflow relationships and EVA – method 4a	Although the WRZ contains hydrologically vulnerable sources, available headroom is more than twice Target Headroom throughout the WRMP19 planning horizon, and WRMP19 resilience testing indicates that risks are low. Method 4a is therefore acceptable.
North Ceredigion	Risk is low, but needs to be checked, so DRS assessment is required.	Flow perturbation using rainfall/inflow relationships and EVA – method 4a	Some risk was identified in the EVA resilience testing report, although not at the 1 in 200 year level when demand was set to equal DO. Available headroom is over four times Target Headroom throughout the WRMP19 planning period. A simpler method is therefore appropriate. **Updated position: Initial testing showed that there was no risk of any failures occurring under any statistically plausible drought event. Therefore, no further assessment was undertaken.**
Alwen Dee	Unlikely to require response surface.	Re-analysis of the EVA based on updated WRAPSim results.	Although the available headroom is less than twice Target Headroom in the WRMP, the relatively large size of the reservoir and nature of inflows, means that the potential yield of the reservoir is much higher than DO, and the supply/demand balance is much more sensitive to increases in demand than it is to changes in drought severity. The long record and good fit on the EVA also means that there is a good degree of confidence in the resilience assessment. The change from worst historic to 1 in 200 year event indicated there is no risk of emergency storage breach under plausible drought scenarios. Alwen Dee has therefore been excluded based on the fact that supply failures are not anticipated under any plausible drought scenarios. Some updates to the WRAPSim

			model are currently being carried out, and the EVA will need to be updated to check that the risk is still too low to warrant a full DRS. **Updated position: confirmed DRS not required see Section 4.3**.
Blaenau Ffestiniog	Unlikely to require response surface.	Simple review of risk given licence change	Resilience testing for WRMP19 indicates minimal risk. Available headroom is more than three times Target Headroom. **Updated position: confirmed DRS not required – see Section 4.5**
Brecon Portis WRZ	Secondary assessment – based on availability of flows in the Usk	Bespoke check on risk; it is unlikely that a DRS will be needed or is technically relevant	The abstraction at Brecon is only at risk if the Usk reservoir is unable to release to the river during extreme drought events. This would be apparent from the SEWCUS analysis. The proposed method is therefore to review the SEWCUS WRAPSim results to determine if there is any risk. For the Portis supply, there is no plausible drought scenario where Usk reservoir could not meet this demand. **Updated position: confirmed DRS not required – see Section 4.10.**
Mid & South Ceredigion	Unlikely to require response surface.	'Sense' checking of the WRMP19 WRAPSim outputs and hence the potential for localised risks is the only proposed activity given the very low risks.	The WRMP19 resilience testing showed that, even where the demand is set to equal DO, it is unlikely that there would be any deficit unless extremely high drought return periods are tested. Available headroom is over three times Target Headroom throughout the WRMP19 planning period. If the risk is caused by hydrology, then this will be reviewed initially using simple variance based analysis. **Updated position: further work was undertaken to improve the hydrology for this RZ, however this did not lead to a change in the level of drought resilience – see Section 4.8.**
Bala	No response surface required	N/A	Available headroom is more than four times Target Headroom and the WRMP19 resilience analysis indicated there is no risk of emergency storage breach under plausible drought scenarios.
Dyffryn Conwy	No response surface required	N/A	WRMP19 resilience testing indicates there is no risk of emergency storage breach for Llyn Colwyd or the WRZ aggregated storage under plausible drought scenarios. Available headroom is more than twice Target Headroom throughout the WRMP19 planning period.
South Meirionnydd	No response surface required	N/A	WRMP19 resilience testing indicates there is no risk of emergency storage breach under plausible drought scenarios. Available headroom is over four times Target Headroom throughout the WRMP19 planning period.

Elan Builth	No response surface required	N/A	Although drought can affect the Elan Valley system, this affects the main supply to Severn Trent, and there is no risk to the much smaller Welsh Water abstraction. For the Builth abstraction, there is no plausible drought scenario under which flows in the River Wye would fall below the abstraction licence.
Hereford CUS	No response surface required	N/A	No plausible drought scenario under which flows in the River Wye would fall below the abstraction licence.
Llyswen	No response surface required	N/A	No plausible drought scenario under which flows in the River Wye would fall below the abstraction licence.
Monmouth	No response surface required	N/A	No plausible drought scenario under which flows in the River Wye would fall below the abstraction licence.
Whitbourne	No response surface required	N/A	No plausible drought scenario under which flows in the River Teme would fall below the abstraction licence.
Ross on Wye	No response surface required	N/A	The risk entirely depends on the Severn Trent bulk supply, which is not drought dependent.
Pilleth	No response surface required	N/A	There is no data on the groundwater source, but also no anecdotal evidence that it is drought vulnerable and Available headroom is over three times Target Headroom throughout the WRMP19 planning period.

3. Drought response surface approach

As detailed in Section 1, DRS were completed for both a baseline and climate changed position. The methodology used to generate the baseline DRS is described in Section 3.1 and the approach for incorporating climate change impacts in Section 3.2.

3.1. Baseline DRS methodology

3.1.1. Key Design Parameters

The key design parameters used for the generation of DRS are shown below in Table 3-1.

Table 3-1 - Summary of Input Definitions

Input	Specification and Source of Data
Demand (Ml/d)	Set to equal: Forecast 2019/20 Dry Year Annual Average (DYAA) DI + Target Headroom + Outage + Process losses + Raw water losses.
Scenarios to run	All WRZs analysed for 6, 12, 18, 24, 36 and 48 month durations unless otherwise noted. Analysis based on period ending August and September, or September and October, unless otherwise noted.
Surface Water flows	Timeseries for each relevant source – length and nature vary according to method
Groundwater / other source capabilities	Set to the value used in the WRMP19 DO runs
Exports / Imports	Set to the values used in the WRMP19 DO runs
Exceptional Items	E.g. any demand nodes where additional uplifts are required to reflect localised issues such as higher outage risk; bespoke for each WRZ

As WRAPSim cannot run very large data sets, the number of drought events run through it had to be limited, irrespective of the method used to generate the synthetic events. Based on the nature of the drought vulnerability in the DCWW region as a whole, the two matrices in Table 3-2 and Table 3-3 were developed.

For each drought year there needed to be a suitable ‘warm up’ and ‘cool down’ period, which ensured that there was no impact from one drought into the next. Definitions of the number of years that were used when generating the overall ‘drought library’ is provided in Parts 2 of Table 3-2 and Table 3-3. Applying those rules meant that 571 years’ worth of data needed to be run through the behavioural models for higher risk WRZs, compared with 237 years’ worth of data for the lower risk WRZs.

Table 3-2 also provides the number of droughts selected for higher risk WRZs, while part 1 of Table 3-3 provides the number of droughts selected for lower risk WRZs where DRS still needed to be generated. The ‘return period band’ was translated to actual deficit percentages, which depend upon the rainfall characteristics of the WRZ.

Table 3-2 - Number of Droughts Required in each Return Period Band for Higher Risk WRZs

Matrix Part 1 - Number of Droughts Selected for Each DRS Cell

Rainfall Deficit Return Period Band (1 in X years)	Drought Duration				
	6m	12m	18m	24m	48m
100	4	5	5	4	3
200	5	6	6	6	4
500	5	6	6	6	4
1000	4	5	5	4	4
5000	2	2	2	2	2

Matrix Part 2 - Guidance on Timeseries Extraction for Each Drought

Drought duration	6m	12m	18m	24m	48m
Years warm up	2	2	2	2	1
years cooldown	1	1	1	1	1
Duration of each event (years)	4	5	5	6	7

Total years in band	80	120	120	132	119
Total years in drought library	571				

Table 3-3 - Number of Droughts Required in each Return Period Band for Lower Risk WRZs

Matrix Part 1 - Number of Droughts Selected for Each DRS Cell

Rainfall Deficit Return Period Band (1 in X years)	Drought Duration				
	6m	12m	18m	24m	48m
100	2	2	2	1	1
200	2	4	4	2	2
500	2	3	3	1	1
1000	1	2	2	1	2
5000	1	1	1	1	1

Matrix Part 2 - Guidance on Timeseries Extraction for Each Drought

Drought duration	6m	12m	18m	24m	48m
Years warm up	2	2	2	2	1
years cooldown	1	1	1	1	1
Duration of each event (years)	4	5	5	6	7

Total years in band	32	60	60	36	49
Droughts in 500 year sequence	237				

3.2. Climate Change impacted DRS

3.2.1. Introduction and General Application

The scope of analysis for this project includes both a baseline (2019) analysis and a 2030 position. For the 2030 position it was proposed that climate change was specifically included in the analysis. Climate change is excluded from the baseline scenario so that the expected impact in the 2030 scenario can be clearly seen. The inclusion of climate change is briefly considered in the DVF report, but specific details of the methods used depend on the exact data and model availability for individual water companies. For this project, climate change was included into the assessment using the following general rules:

- The percentage deficit bands in the DRS still represent the deficit from the 1961-1990 baseline period.
- The return period estimates of each deficit/duration band were adjusted according to climate change - i.e. where climate change reduces rainfall for a given duration, then that means the return period of a given deficit became smaller than in the baseline assessment. For example, for a 12-month duration a 40% rainfall deficit may have a return period of 1 in 100 years in the baseline, but under climate change this could reduce to a 1 in 50 event, so would lie on the 1 in 50 line for the 2030 DRS.
- As flows reduce due to increasing PET there were more days of failure at a given level of demand and rainfall deficit. The impact of increasing PET is therefore implicitly expressed through changes in the number of days of shortfall in the 2030 version of the DRS.

3.2.2. Detailed Requirements

The exact method used to apply climate change to the DRS needed to vary slightly between the following categories of WRZs:

- WRZs where new hydrological modelling was run for the baseline analysis: in that case it was simplest to apply change factors directly to rainfall and PET to determine changes in flows according to climate impacts.
- WRZs where direct stochastic flow generation was used and there was no reservoir storage involved: the lack of rainfall-runoff modelling for the stochastic analysis means that it was more appropriate to use the HR Wallingford flow perturbation factors and combine these with simple delta changes in rainfall deficit.
- WRZs where existing flows were taken from the WRMP19 analyses: it was more appropriate to rely on the HR Wallingford flow perturbation factors that were developed for WRMP19.
- Low risk WRZs where flow perturbation was applied based on rainfall/inflow relationships: flow perturbation factors developed for WRMP19 using the Future Flows scenarios were applied in this case with equivalent precipitation change factors calculated from the corresponding Available Precipitation Future Flow scenario at that location (downloaded as part of this project).

Details of how the general requirements were applied to the WRZs that require assessment for this study are provided for each WRZ in Section 4, using flow diagrams as per the baseline analysis.

3.3. Catchmod modelling

Where a DRS was based on stochastically generated rainfall (NEYM, Barmouth and Lleyn Harlech) a rainfall-runoff model was required to convert this rainfall into flow. Unfortunately, previous experiences of using the existing models have demonstrated that it is impractical to simulate very long (i.e. stochastic) rainfall sequences using the Hysim software. Therefore, as part of this project new Catchmod models were developed. The Python coded version of the software, PyCatchmod, was then used to simulate stochastic flow for use in the drought vulnerability assessment.

As part of the same exercise Catchmod models were also developed for Mid and South Ceredigion. In this WRZ, however, the DRS was based on EVA of historic hydrology so there was no requirement to process stochastically generated rainfall. The objective was to use models to try to improve the hydrological representation of inflows into the Teifi Pools reservoir group (Section 4.8).

All of this Catchmod development work is reported separately[2].

[2] Drought Vulnerability Framework Hydrological Update (Atkins, 2019)

4. Drought vulnerability assessment

4.1. North Eryri Ynys Môn

4.1.1. Key Modelling Assumptions

The North Eryri Ynys Môn (NEYM) WRZ consists of five raw water storage reservoirs, two of which are located on Anglesey and the remaining three on the mainland. The system is operated conjunctively whereby water is generally transferred from the mainland to Anglesey when supplies are available and then reduced in line with control rules. Following network improvements made in summer 2018, DCWW now has the ability to transfer some water from Anglesey to the mainland.

The overall DVF analysis therefore considered the WRZ storage as being conjunctive and hence 'failure' is defined as being where the reservoirs fall below an aggregated emergency storage value. Table 4-1 below presents the key assumptions used for the DVF analysis.

Table 4-1 - Summary of Key Modelling Assumptions

Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	42 Ml/d DYAA	This reflects a significant available surplus in the WRZ. The demand value is based on DI, plus Target Headroom, plus outage and process losses. Profile based on WRAPSim.
Durations Analysed	6, 12, 18, 24 and 48 months	Storage relies on high rainfall in the mountains, so can be vulnerable to quite short duration, but very high intensity, drought events
Months Ending Analysed	September, October	Reflects the occurrence of minimum storage levels in the historic record
Failure Criterion	Emergency storage failure	Failure of emergency storage on aggregate across all 5 reservoirs (emergency storage = 30 days demand)
Climate Change Scenario Used	Ensemble weighted average	As the analysis involved generation of new weather and flow data sets, perturbation according to WRMP19 ensemble averages was possible in this WRZ.

4.1.2. Methodology: Baseline

Due to the perceived level of drought risk in the WRZ, it was analysed using DVF method 1b (stochastic weather and flow generation). The impacts on yield and system failure needed to be run through WRAPSim, so a 'drought library' approach was taken to sample representative droughts from the full stochastically generated flow and rainfall data set.

A summary of the methodology that was adopted for NEYM is provided in Figure 4-1.

1. Generate a spatially coherent stochastic rainfall and PET record for all catchments. Generate associated flows using Catchmod
2. Assign each year a rainfall deficit by scenario (based on the average stochastic rainfall for that year). Generate rainfall deficit/probability curves from the stochastically generated data set.
3. Use the lookup matrix to select an appropriate number of drought events in each rainfall deficit/duration for testing in WRAPSim
4. Generate a drought library timeseries input, based on the selected drought events and the lookup table of warm up and cool down requirements for the different drought durations.
5. Run the 500 year drought library through WRAPSim. Review results and examine both aggregate failures against emergency storage and individual reservoir responses.
6. Plot the DRS based on the number of days failure and the calculated rainfall deficit for each scenario for each stochastically generated year.

Figure 4-1 - Summary of Analysis Method

Outputs and comments from Stages 1 to 6 are provided below.

Stage 1: Generation of Stochastic Weather and Flows

The process used for stochastic weather generation is the same as that used for Pembrokeshire for WRMP19, full details can therefore be found within the WRMP19 technical appendix. For NEYM the existing Hysim models were converted into Catchmod and re-calibrated (see separate Hydrology report[2])

Stage 2: Generation of Rainfall Deficit/Probability Curves

As the stochastically generated weather set contained over 12,000 years of record, the deficit/probability curves were created by inverse ranking of the generated rainfall data set.

Stages 3 and 4: Generation of the Drought Library

NEYM has been assessed as a higher risk WRZ and so each drought library that was run through the WRAPSim model consisted of approximately 500 years' worth of generated data. This drought library was sampled from the full stochastic data set based on the matrix shown in Table 3-2.

The number of droughts involved was purely a pragmatic decision that balanced the need to fully explore the drought risk in each DRS cell against the run time involved in WRAPSim. As shown, all events up to 1 in 1000 years return period had at least 4 droughts explored for each combination of rainfall severity and duration, which should be sufficient to identify if there is a significant risk for that type of drought.

Stages 5 and 6: Generation of Failure Data and the Final DRS

The drought libraries were run through WRAPSim and the volumetric responses in each reservoir at the selected level of demand (Table 4-1) was recorded. These responses were then examined in a post processing stage to assess the duration of emergency storage failures for each drought event.

4.1.3. Methodology: 2030s Climate

The impact of climate change on rainfall deficits and flows was carried out using the general methodology shown in Figure 4-2. As the flows were generated from the baseline stochastic weather data set, the impact of climate change on flows and hence the drought library could be calculated directly through the perturbation of rainfall and PET data.

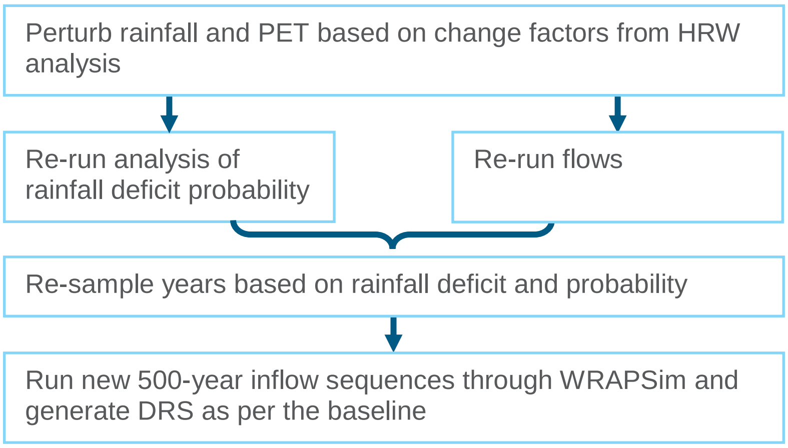


Figure 4-2 - Methodology for the Application of Climate Change

4.1.4. Results

Drought Risk Analysis

For the baseline (i.e. no climate change) scenarios the individual storage reservoirs behaved reasonably conjunctively, even under very severe drought scenarios. Figure 4-3 and Figure 4-4 show storage on an aggregate level for the periods ending September and October. The red line represents the aggregate level of emergency storage in each of the reservoirs. Failures of emergency storage on an aggregate level only tend to occur when Llyn Alaw falls below the emergency storage line as this reservoir accounts for over half the available storage in the NEYM zone. It is these failures that drive the DRS detailed in the following section.

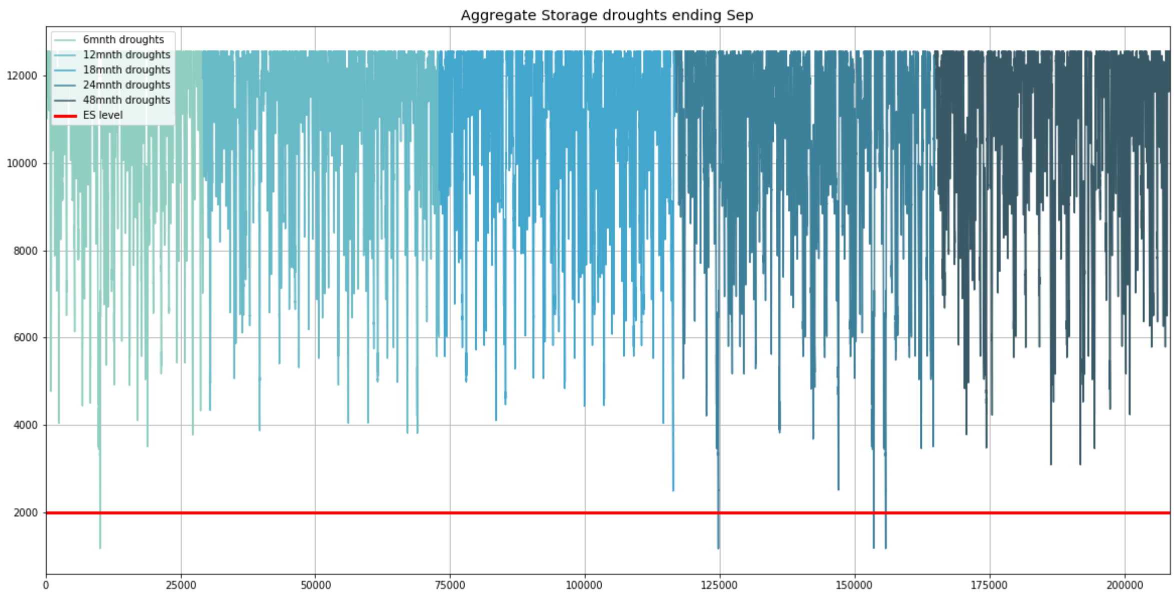


Figure 4-3 - Aggregate Drought Library Results for period ending September

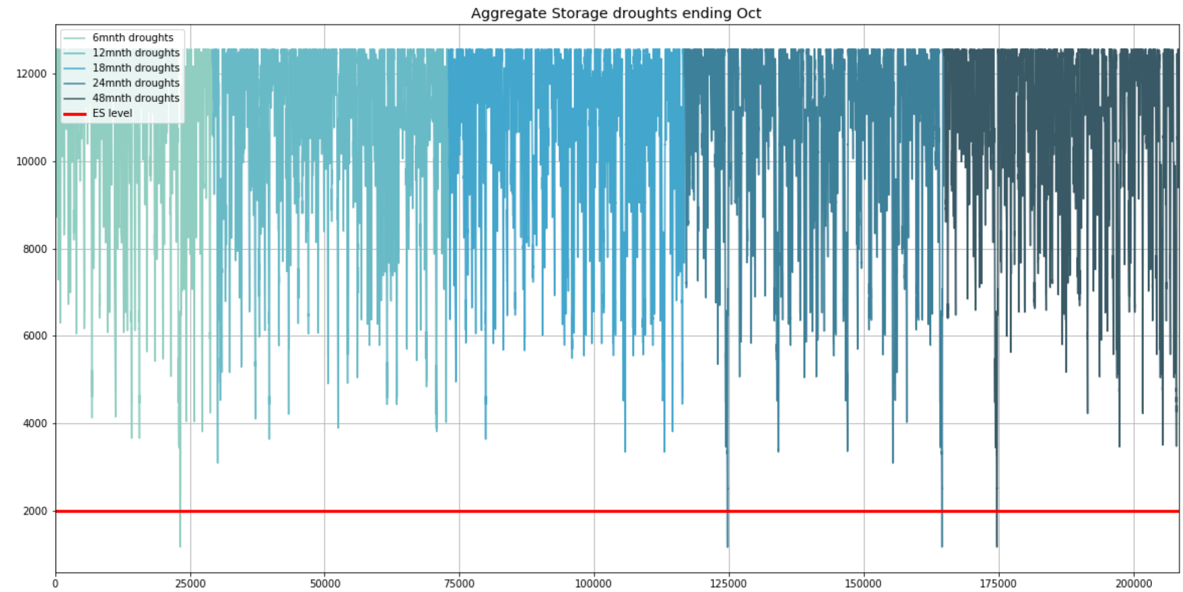


Figure 4-4 - Aggregate Drought Library Results for period ending October

Although the system behaved reasonably conjunctively, there is some variability between the reservoirs with some being drawn below their nominal operationally preferred minima (see Figure 4-5 to Figure 4-9 below for outputs of the period ending October). This is most notable in the smaller reservoirs; Llyn Marchlyn Bach, Llyn Cefni and Llyn Cwellyn.

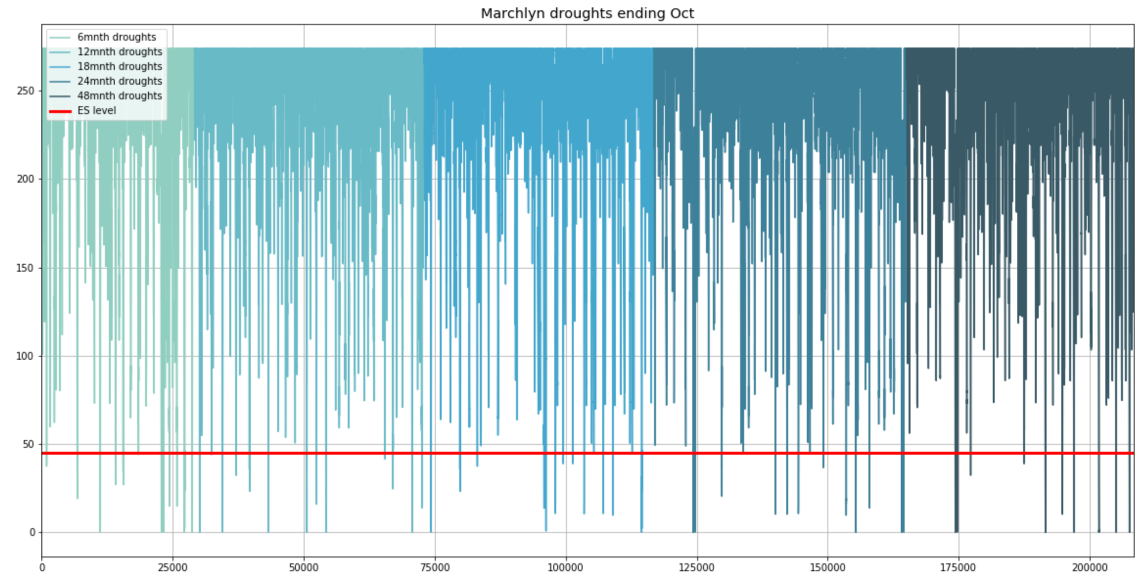


Figure 4-5 - Drought Library Results for Llyn Marchlyn Bach

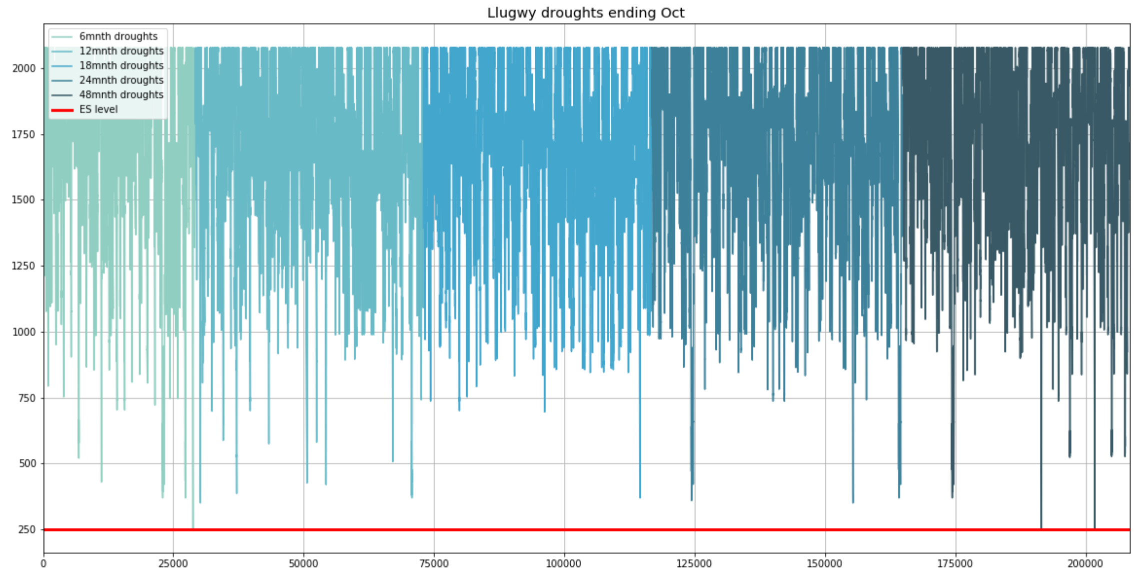


Figure 4-6 - Drought Library Results for Llyn Ffynnon Llugwy

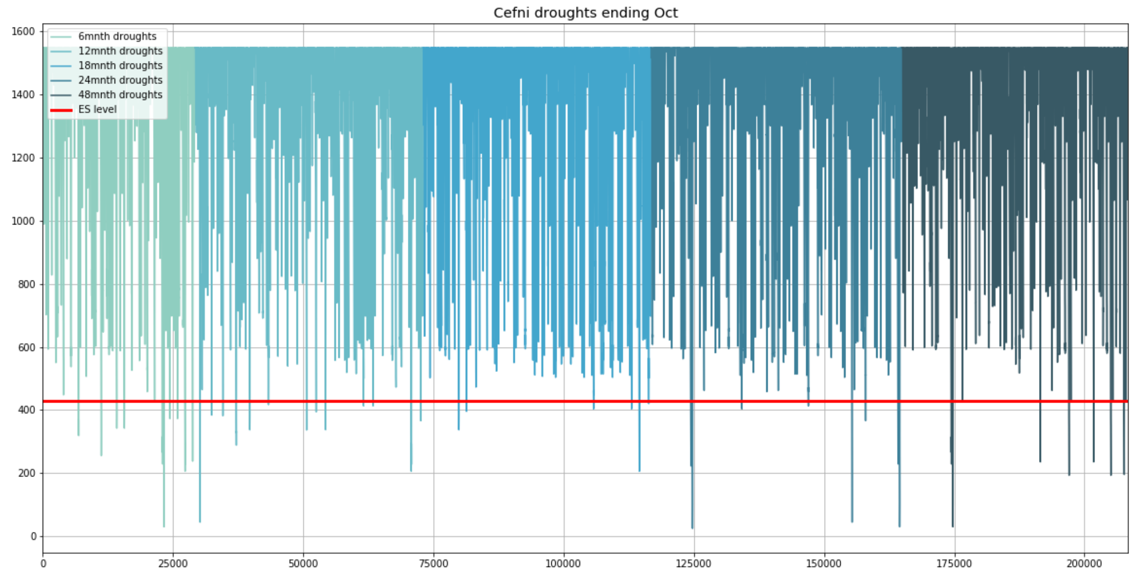


Figure 4-7 - Drought Library Results for Llyn Cefni

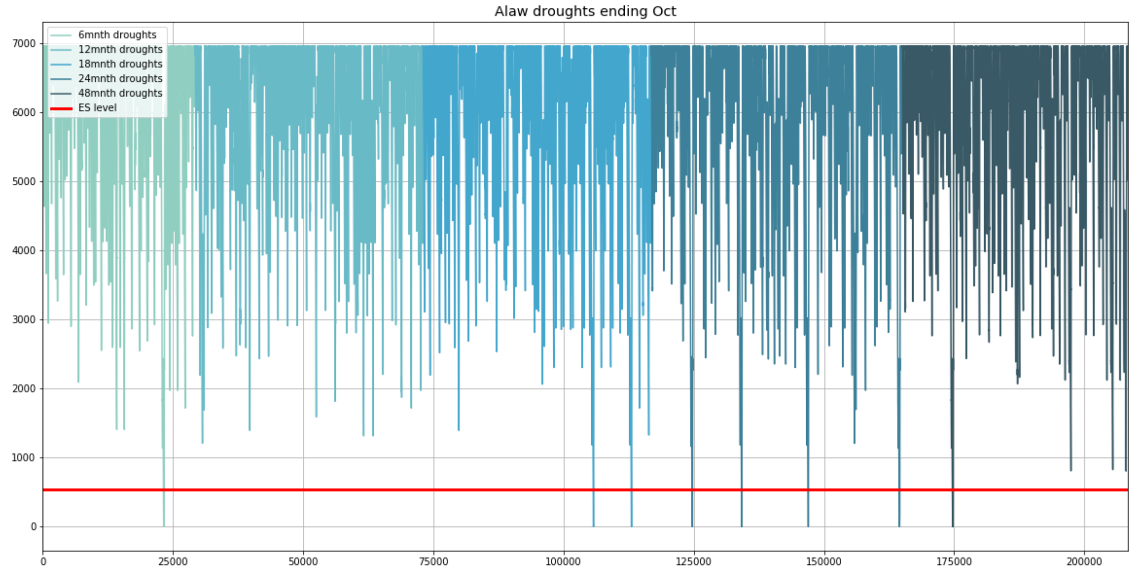


Figure 4-8 - Drought Library Results for Llyn Alaw

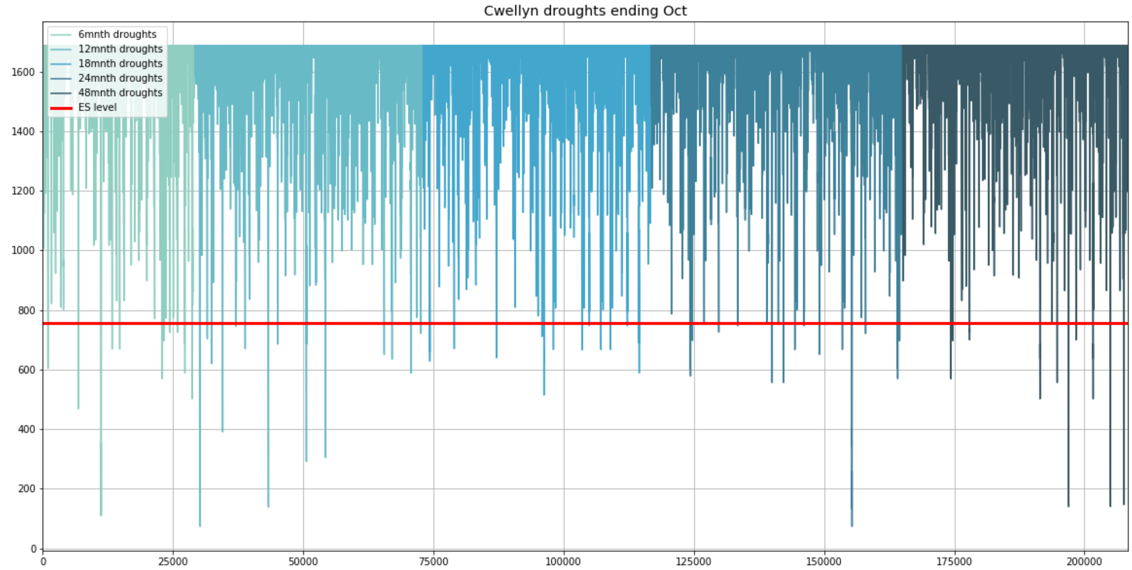
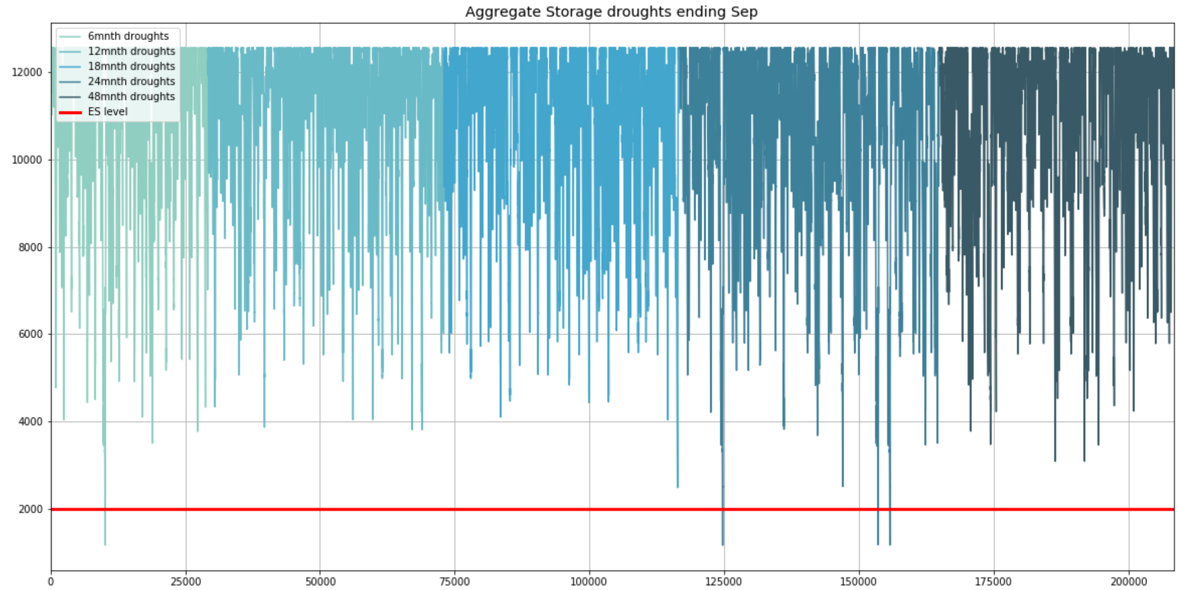


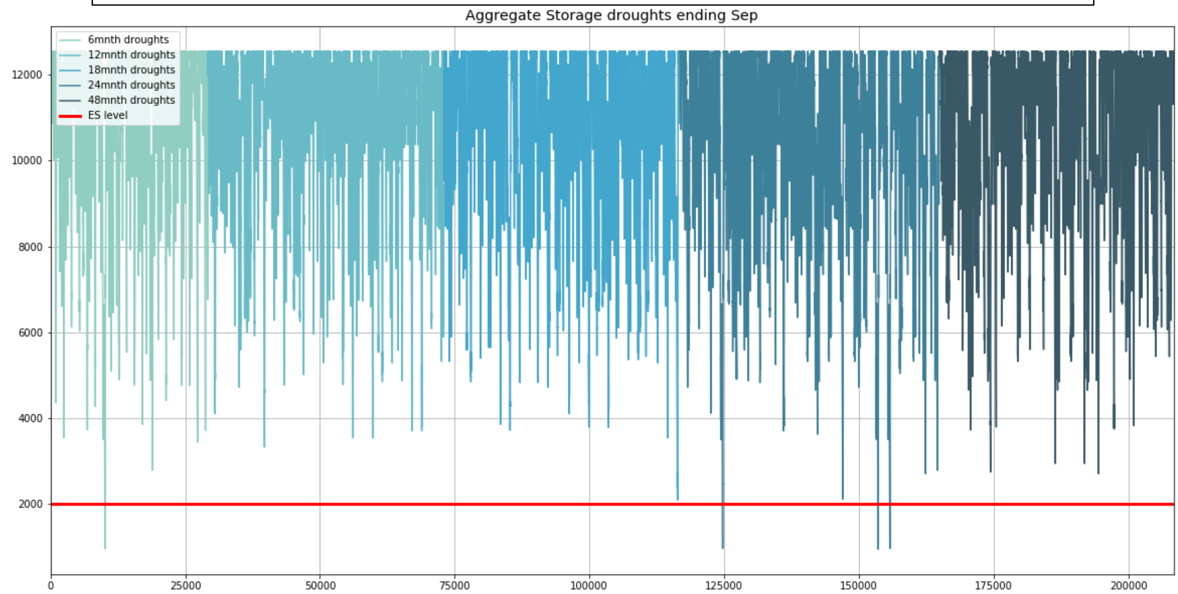
Figure 4-9 - Drought Library Results for Llyn Cwellyn

Under the 2030s climate change scenario, the main impacts on risk of failure are for the droughts that end in September, which are driven by the generation of steeper summer recessions (in other words, by October it is much more likely that rainfall will have occurred to restock reservoir levels). A comparison of the aggregate storage for September with and without climate change is provided in Figure 4-10 below. Because flows tend to increase under the central climate change scenario in October, then the risk of 'failure' under each event is very similar.

It should be noted that, under climate change the risk of a given deficit (and hence one of the drought library events) occurring does tend to increase as well. This is discussed in the DRS section below.



Storage plot without climate change



Storage plot with 2030 climate change

Figure 4-10 - Comparison of Llyn Alaw Storage Plots with and without climate change for the Selected Drought Library – 'Ending September' scenario

Drought Response Surfaces

As shown in Figure 4-11, for the baseline scenario there were only a few droughts that generated failures against the zonal aggregated emergency storage, all of which related to longer duration events (18 months plus) due to storage in the Anglesey reservoirs being quite large in relation to the level of abstraction simulated. As shown in the previous section, some of the shorter duration events did apparently cause failures at the aggregate level, but that was because they represented the worst 6 months in a longer event, and there were no instances where events of less than 12 months would, in themselves, create a risk of aggregate emergency storage failure. As there were very few droughts that actually caused emergency storage failures, each one was investigated to check the nature of failure and determine the underlying duration driver for that failure.

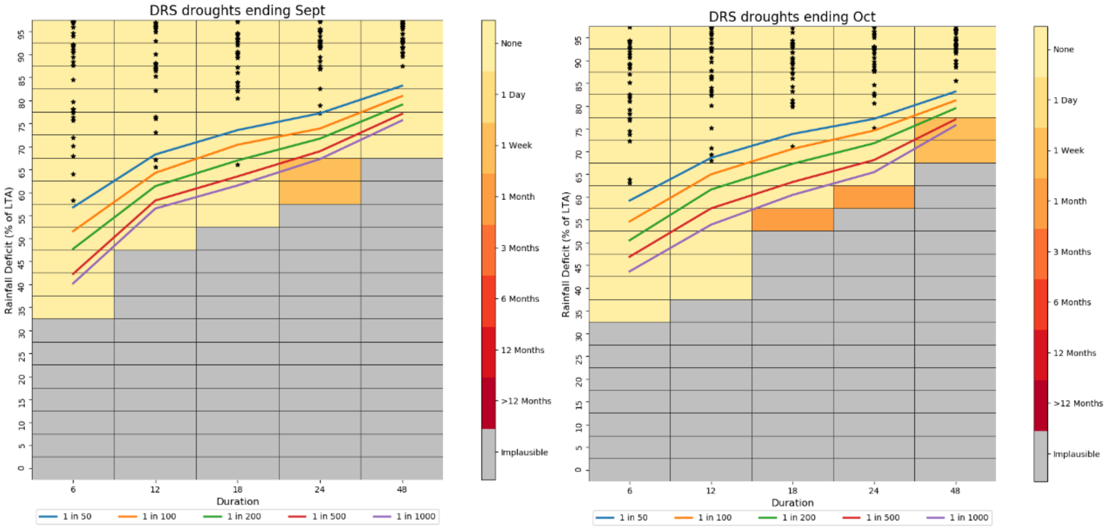


Figure 4-11 Drought Response Surfaces (smoothed) – no climate change

This confirms that due to the current large surplus in the WRZ the risk of failure on an aggregate basis is low (1 in 500 – 1 in 1000), and will only tend to occur for 18-24 month type events. Although the 48 month event for the 'ending October' scenario contains some failures, analysis of the individual events confirmed that this was entirely driven by the inclusion of a shorter (24 month) event within the four year period – i.e. it highlights that a longer 1 in 500 type 48 month event may well incorporate a more severe, shorter term, event that can cause failure.

As shown in Figure 4-12, the inclusion of climate change causes a notable increase in risk for the droughts that end in September under the 24 month scenario. The shape of the DRS also changes notably for the 12 and 24 month events, particularly for the droughts that end in September, with the maximum plausible deficit and probability of deficits reducing. This is a feature of the increase in winter rainfall and decrease in summer rainfall, which are expressed as deficits from the pre-climate change (stationary) climate. As winter rainfall is higher proportionally in the baseline and tends to be even higher under climate change, then this means that the apparent severity of droughts that includes the winter period tends to reduce when compared to the stationary baseline. However, those droughts will include more severe summer recession periods. This means that the risk of failure increases at the same time as the range of deficits reduces. The increase in risk for the 24 month event therefore needs to be viewed in context as to what is actually happening, in that the risks from the summer during those longer periods are what is driving the increase in risk.

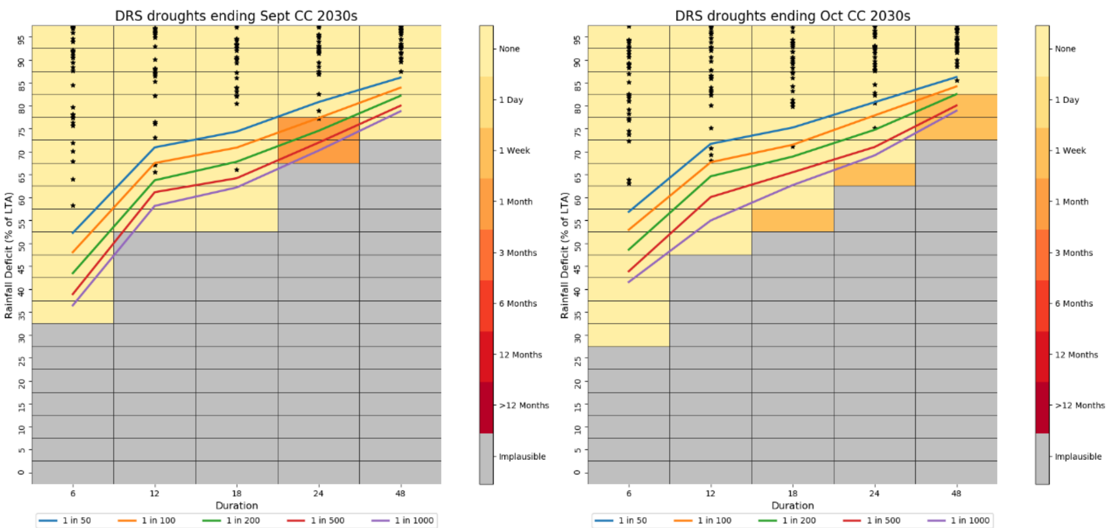


Figure 4-12 - Drought Response Surfaces (smoothed) – with 2030s climate change

Figure 4-12 suggests that risks of failure could occur at somewhere between the 1 in 100 and 1 in 200 year rainfall deficit severity for September ending 24 months events under 2030s climate change. However, because there are still very few droughts that actually fail within the Drought Library, and droughts have been ordered into 5% deficit bands, the exact return period/deficit risk under climate change for the period ending September would require more analysis (i.e. more drought libraries and WRAPSim runs) at a finer level of granularity (i.e. order rainfall into 2% bands) before the level of risk could be confirmed.

4.2. Clwyd Coastal

4.2.1. Key Modelling Assumptions

Approximately half of the Clwyd Coastal WRZ is supplied from the Afon Aled river regulation scheme. Two upland impounding reservoirs (Llyn Aled and Aled Isaf) provide regulation releases to support abstraction from the river at Bryn Aled. The majority of the WRZs remaining supply comes from a series of boreholes at Llanerch. There is also a small spring source at Trecastell. Current knowledge suggests that the spring / boreholes are not vulnerable to drought and so this vulnerability assessment concentrates on the Aled reservoir system as this is the primary indicator of drought in the WRZ.

The zonal water resource arrangement is relatively complex and so it was necessary to carry out flow generation as part of the drought vulnerability assessment. However, due to the low risk nature of the WRZ this was completed using one of the simpler DVF assessment methods. Figure 4-2 below presents the key assumptions used for the DVF analysis.

Table 4-2 - Summary of Key Modelling Assumptions

Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	24.9 Ml/d DYAA	Based on DI, plus Target Headroom, plus outage and process losses. Profile based on WRAPSim.
Durations Analysed	6, 12, 18, 24 and 48 months	Storage relies on high rainfall in the mountains, so can be vulnerable to quite short duration, but very high intensity, drought events
Months Ending Analysed	September, October	Lowest flow periods according to historic data – some uncertainty over individual reservoir responses so three months ending tested in this case
Failure Criterion	Duration where storage is below emergency	Failure of emergency storage (emergency storage = 30 days demand plus regulation flow plus compensation flow)
Climate Change Scenario Used		This represents the 50th percentile UKCP09 scenario (central estimate) used to determine deployable output impact in WRMP19.

4.2.2. Methodology: Baseline

Clwyd Coastal is a lower risk WRZ so we adopted method 4a according to the DVF – i.e. re-sampling and scaling of the historic reservoir inflow record. A summary of the methodology that was adopted for Clwyd Coastal is provided in Figure 4-13 below. Outputs and comments from Stages 1 to 6 are provided in the following sections.

1. Calculate rainfall deficit/total flow relationships for all scenarios using the historic record.

2. Generate a stochastic monthly average timeseries across all of the WRAPSim input catchments. For each stochastic year, assign a nominal rainfall deficit for each scenario based on the historical relationship.

3. Use the lookup matrix to select an appropriate number of drought events in each rainfall deficit/duration for testing in WRAPSim

4. Generate a drought library timeseries input, based on the selected drought events and the lookup table of warm up and cool down requirements for the different drought durations.

5. Run the 500 year drought library through WRAPSim. Review results and examine both aggregate 'Big 5' failures against emergency storage and individual reservoir responses.

6. Plot the DRS based on the number of days failure and the calculated rainfall deficit for each scenario for each stochastically generated year.

Figure 4-13 - Summary of Analysis Method

Stage 1: Extreme Value Analysis (EVA) of Rainfall Deficit

Rainfall deficit probabilities for each scenario were generated using the historic record and EVA curve fitting. The process was relatively straightforward and example outputs from that analysis are provided in Figure 4-14.

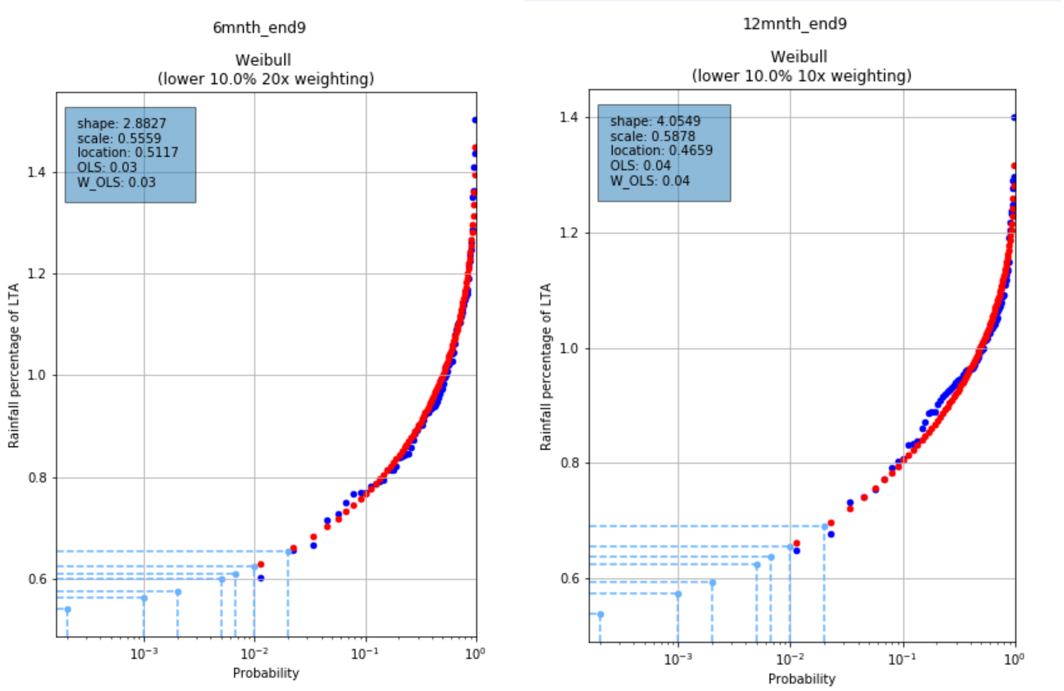


Figure 4-14 - Example EVA Plots for Clwyd Coastal

Stage 2: Calculation of Rainfall Deficit/Flow Relationships

The generation of a stochastic set of reservoir inflows followed the DVF method 4a, whereby flows are generated from the historic record based on regression analysis between cumulative flows and rainfall, which are then used to scale the historic record for specific droughts. Due to the flashy nature of the catchments the correlation between cumulative flows and rainfall was relatively poor in some cases, so it was necessary to ensure that the uncertainty range around the correlation could be sampled to provide a representative range of droughts for each given rainfall deficit. Therefore, both the correlation and the uncertainty range were analysed and defined, to enable the selection process described in Section 4. Examples of the outputs from this analysis are provided in Figure 4-15.

These plots show how the cumulative flow over the defined drought duration and end month (e.g. 6 months ending September) correlate with the rainfall deficits over that time period. The red banding shows the 25th and 75th percentile uncertainty range from that correlation. The yellow dots signify typical dry years used as the basis for flow generation (see Stage 4 below).

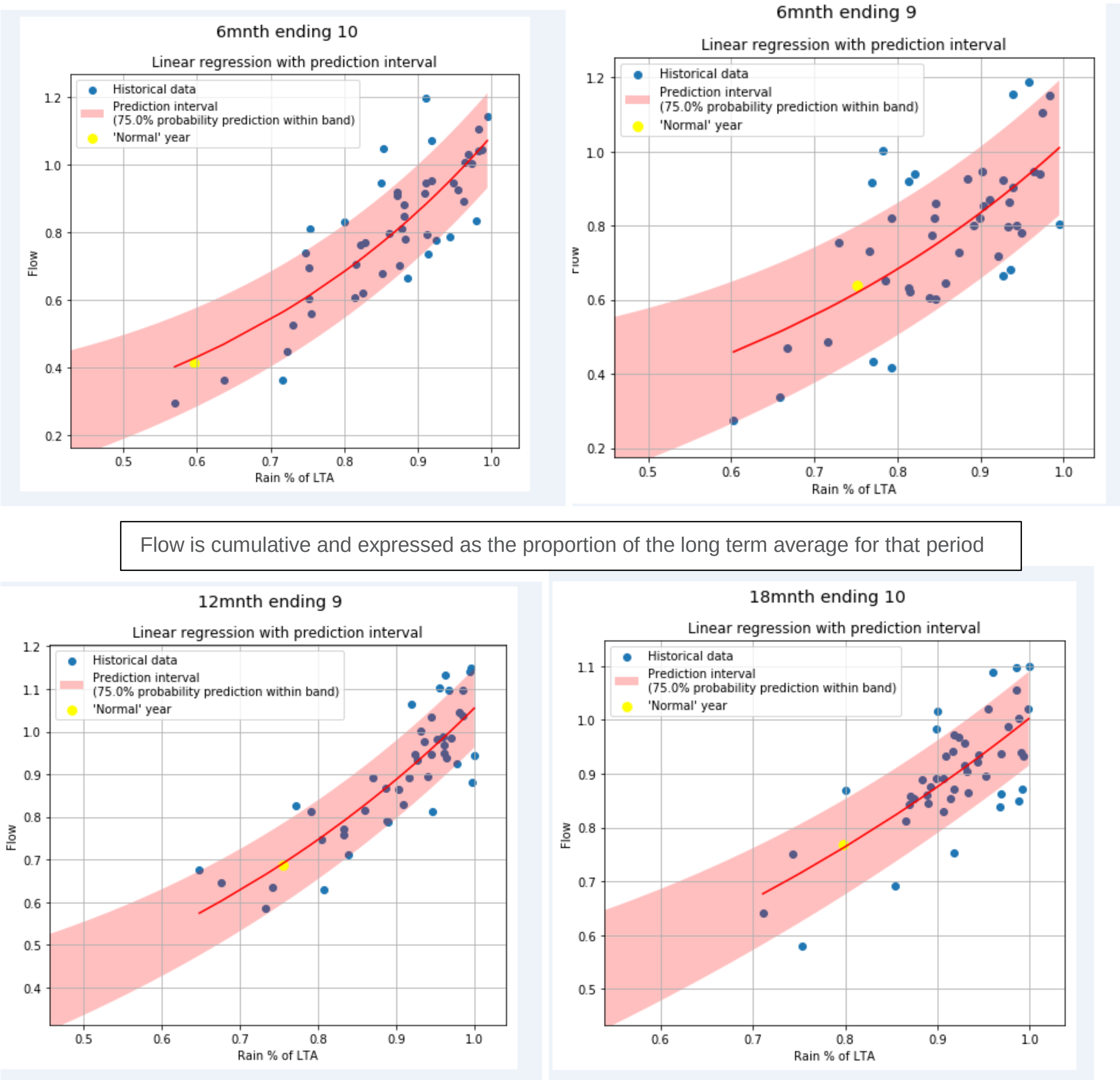


Figure 4-15 - Example Cumulative Flow versus Rainfall Correlation Plots

Stage 3 Selection of Drought Scenarios

Each drought library that was run through the Clwyd Coastal WRAPSim model consisted of approximately 200 years' worth of generated data. The number and severity of droughts included in this drought library was based on the matrix shown below in Table 4-3.

Table 4-3 - Number and severity of droughts included in Clwyd Coastal drought library

Matrix Part 1 - Number of Droughts Selected for Each DRS Cell

Rainfall Deficit Return Period Band (1 in X years)	Drought Duration				
	6m	12m	18m	24m	48m
100	2	2	2	1	1
200	2	4	4	2	2
500	2	3	3	1	1
1000	1	2	2	1	2
5000	1	1	1	1	1

Matrix Part 2 - Guidance on Timeseries Extraction for Each Drought

Drought duration	6m	12m	18m	24m	48m
Years warm up	2	2	2	2	1
years cooldown	1	1	1	1	1
Duration of each event (years)	4	5	5	6	7
Total years in band	32	60	60	36	49
Total years in Drought Library	237				

The number of droughts selected in the drought library was purely a pragmatic decision that balanced the need to fully explore the drought risk in each DRS cell against the limited model functionality of WRAPSim. As shown in Table 4-3, the analysis was able to generate a number of droughts for the shorter duration events that are likely to be the most challenging for the WRZ.

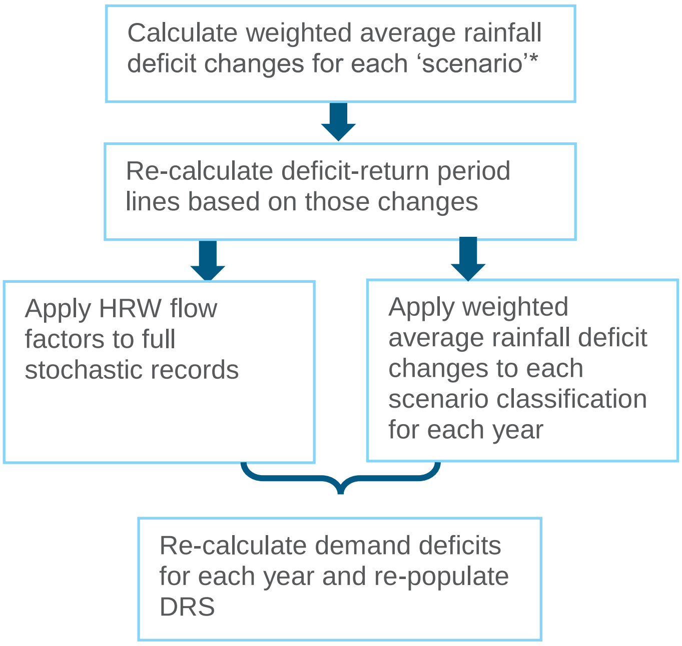
Stage 4: Generation of Flows for the Drought Library

Flows for each drought library were generated based on scaling of the relevant duration from a ‘typical’ year taken from the historic record. The ‘typical’ year was selected as one that was relatively dry but plotted close to the flow/rainfall/regression line. Examples of this are provided in Figure 4-15, as signified by the yellow ‘normal year’ dots. The difference in rainfall deficit between that historic year and the scenario that was being analysed was calculated and this difference was applied to the flow/rainfall deficit algorithm using the following process:

- The difference in rainfall between this ‘typical’ dry year and the drought sequence being generated was calculated.
- The correlation equation between rainfall and flow was used to calculate the flow factor that was relevant to the difference in rainfall. Where there was only a single drought being selected for a deficit/duration band, then this was based on the mean (expected value) of the rainfall/flow regression. Where more than one drought was being analysed for a given deficit/duration cell, then the ratio required to generate a flow equivalent to the 25th percentile (i.e. the lower end of the red band in the Figure 3 examples) were also generated. Where there were three or more then the upper 75th percentile was also selected to provide statistical balance across the deficit/duration cell (and hence the DRS as a whole).
- The calculated flow factors were applied to the ‘typical’ historic year for the drought duration to create the flows for that drought sequence.

4.2.3. Methodology: 2030s Climate

The impact of climate change on rainfall deficits and flows was carried out using the general methodology shown in Figure 4-16.



** the weighted calculation is used to calculate the percentage rainfall change for each duration and month ending scenario, using the HRW rainfall perturbation factors, and the equation:*

$$\% \, change \, in \, rainfall \, for \, scenario \, x = \frac{\sum_{i=1}^{n}(rain * \%change)_{month \, i}}{\sum_{i=1}^{n}(rain)_{month \, i}}$$

Where scenario x = a given combination of duration and month ending (e.g. 6 months ending August)

Figure 4-16 - Climate Change Attribution Method

As WRMP19 used Future Flow scenarios for this WRZ it was necessary to use the Future Flow dataset and extract Available Precipitation (incorporating delays due to water storage as snow and ice) at the four grid locations corresponding to the GEAR rainfall data. The change factors were calculated from the monthly average difference in the available precipitation data between the baseline (1961-1990) and the 2030's period (2020-2049). These factors were then used to calculate the weighted average change for each duration/ending period as per the other WRZs.

4.2.4. Results

Drought Risk Analysis

Plots of the aggregated storage for impounding reservoirs with and without climate change are provided in Figure 4-17 and Figure 4-18 below. As anticipated, the key vulnerability for this WRZ was to short duration droughts as can be seen in the plots below for 6-month duration, ending October. However, the impact is not worsened when climate change effects are accounted for.

There are also risks for 18 month duration droughts, although this was primarily as a result of a very dry summer in either the first or second years (i.e. reflective of 6 month conditions). In the baseline run there were some marginal failures in the 18 month duration droughts ending in September. However, these failures were present in the drought library as part of a cool down period, during which a shorter period drought occurred, and not the 18 month drought period. This means that the failures are not registered in the DRS. The presence of short droughts in the cool down period does not negatively impact the assessment; it is the position at the end of the cool down period that is relevant. The same failures were not present in the climate change run (Figure 4-18); the climate change perturbations can increase as well as reduce inflow.

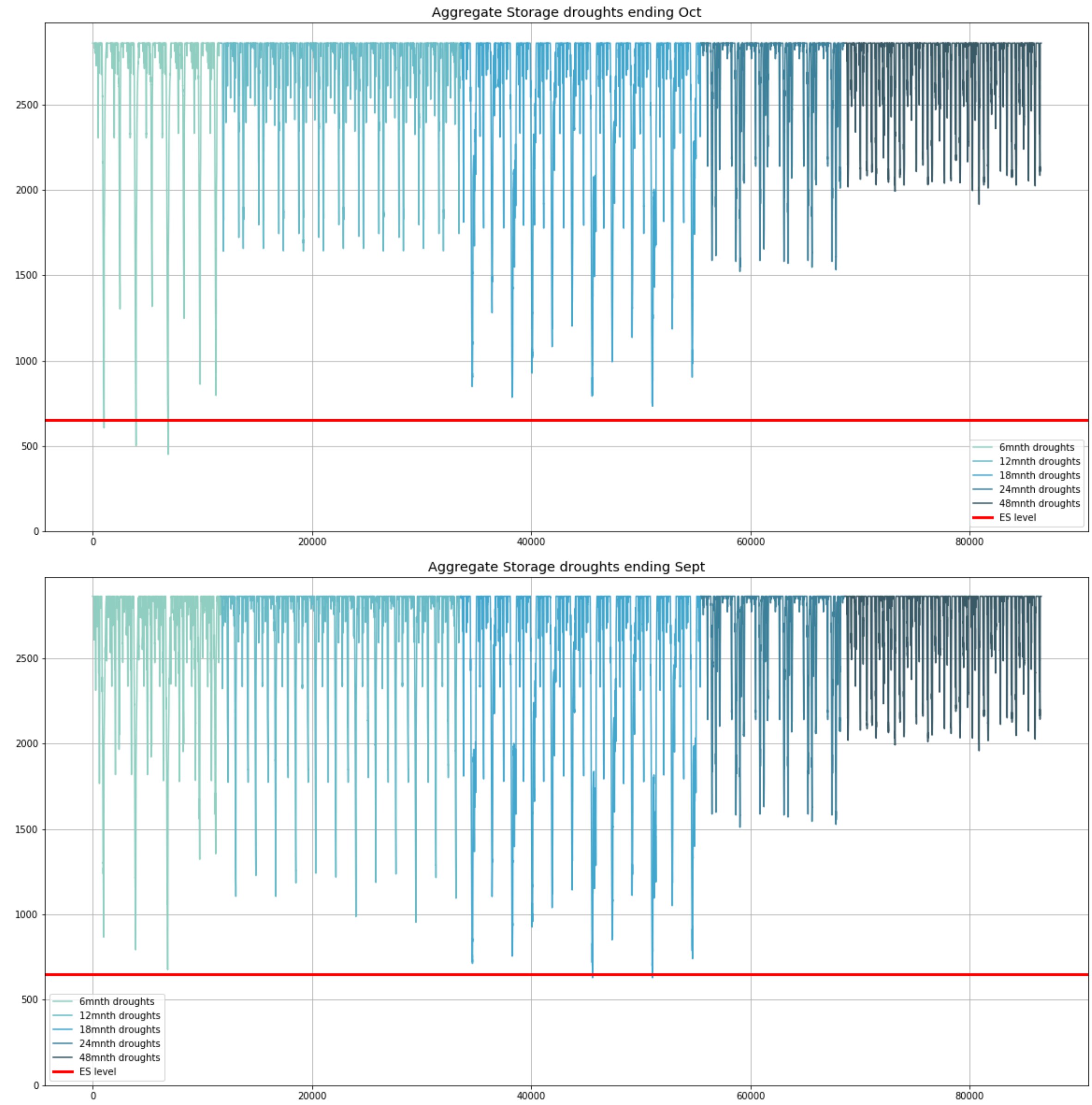
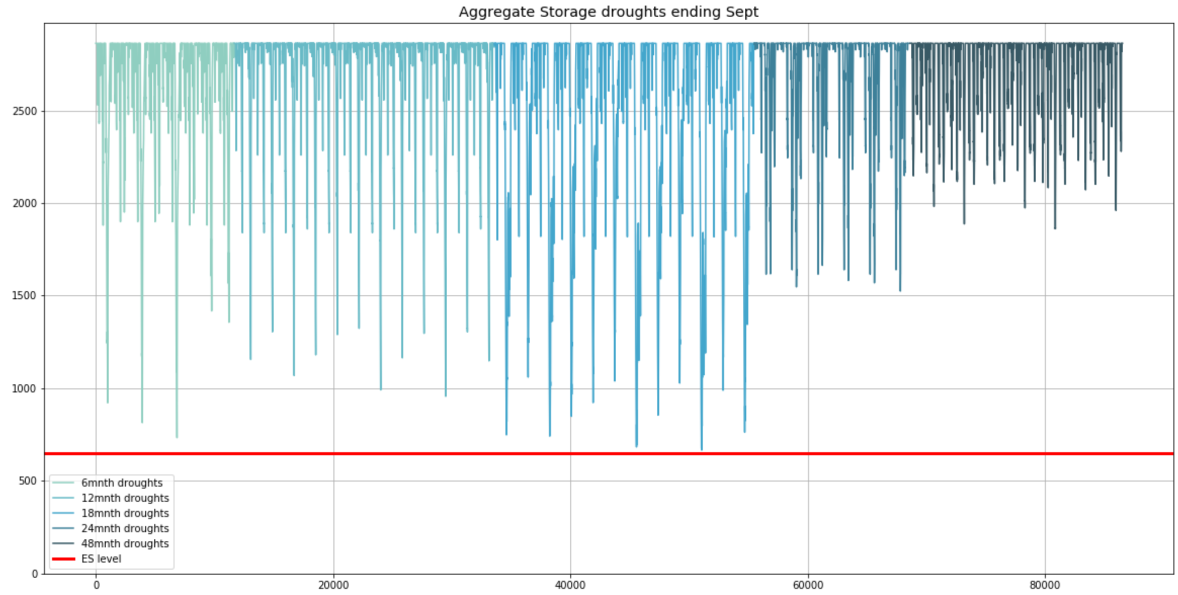


Figure 4-17 - Aggregate Storage Plots for Baseline Drought Events



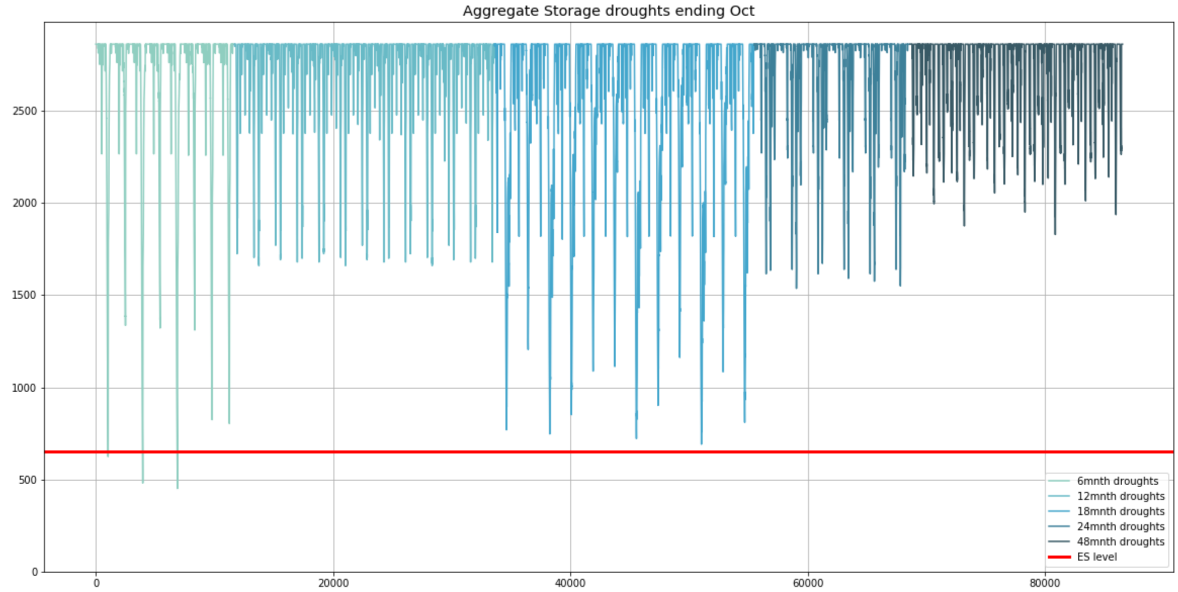


Figure 4-18 - Aggregate Storage Plots for Drought Events with Climate Change

Drought Response Surfaces

As outlined above, there were failures in the 6 month duration droughts that end in October. These; are shown in the corresponding DRS charts in Figure 4-19 and Figure 4-20 below. The failures occur at a rainfall deficit of around 55-50% of LTA, and a return period of 1 in 100 to 1 in 1000 years.

Whilst failures are suggested in the 18 month duration ending September results (Figure 4-17), these were not reflected in the corresponding DRS. As explained above they occurred because of a short duration drought being included in a cool down period, rather than a failure occurring during the 18 month drought itself.

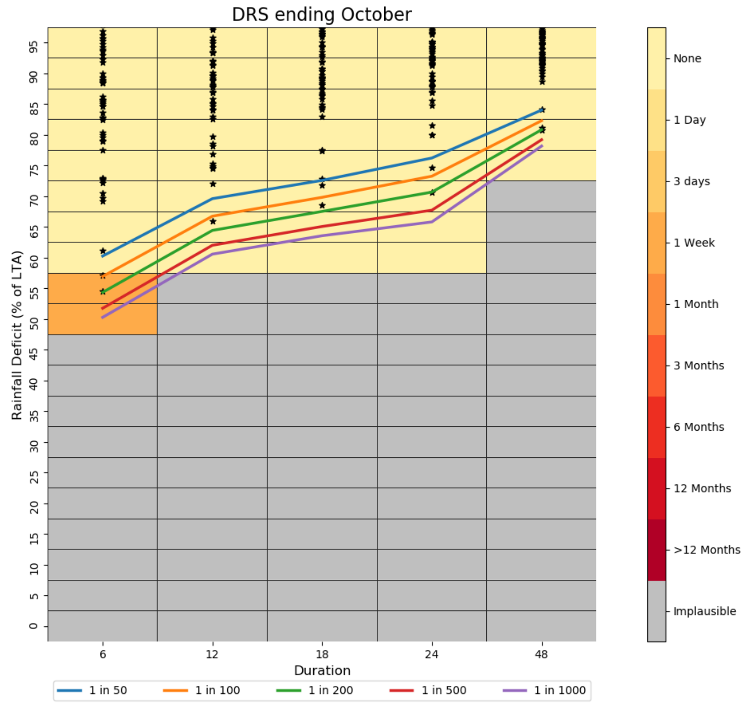


Figure 4-19 - Drought Response Surfaces – no climate change

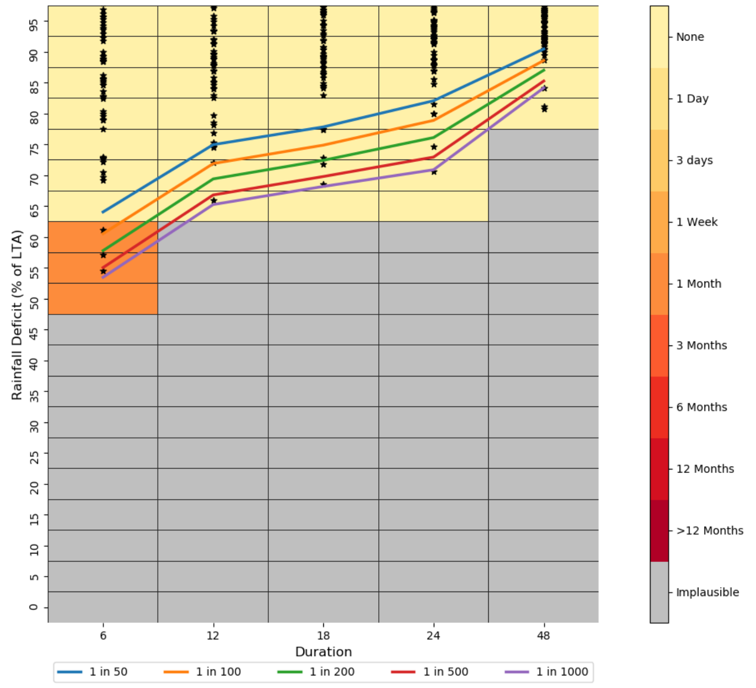


Figure 4-20 - Drought Response Surfaces – with 2030s climate change

4.3. Alwen Dee

This WRZ stretches from the floodplains of the River Dee at Llangollen to the coastal waters at Prestatyn and the industrial complexes on Deeside. There are two water treatment works within the zone; Alwen and Bretton. Alwen is supplied from Alwen reservoir and Bretton is supplied from the River Dee abstraction at Poulton and Bretton boreholes when they are needed to supplement the demand in dry summers.

The River Dee is a regulated river with releases made from Llyn Celyn and Llyn Brenig to support abstractions downstream. The scheme is managed by NRW in accordance with the Dee General Directions.

Previous assessments, focussed on Alwen reservoir, have shown using EVA that the WRZ is resilient to a 1 in 200 year drought event. Although available headroom is less than twice Target Headroom in the WRMP, the relatively large size of the reservoir and nature of inflows, means that the potential yield of the reservoir is much higher than DO, and the supply/demand balance is much more sensitive to increases in demand than it is to changes in drought severity.

4.3.1. Extreme Value Analysis

The long record and good fit of the EVA meant that there was a good degree of confidence in the resilience assessment completed for WRMP19. For the DVF the EVA was updated, initially with the outputs from the latest WRAPSim model, and then from the recently developed Aquator model.

Simulated storage from the Alwen Dee Aquator model, and the 1 in 200 and 1 in 500 year droughts derived by EVA, are all well above emergency storage, with and without climate change applied (Figure 4-21 and Figure 4-22). There is little influence of climate change and the Future Flow scenario that was used (FFQ14) was shown to increase winter inflow. Storage levels for the 1 in 200 and 1 in 500 year return periods are also shown in Table 4-4.

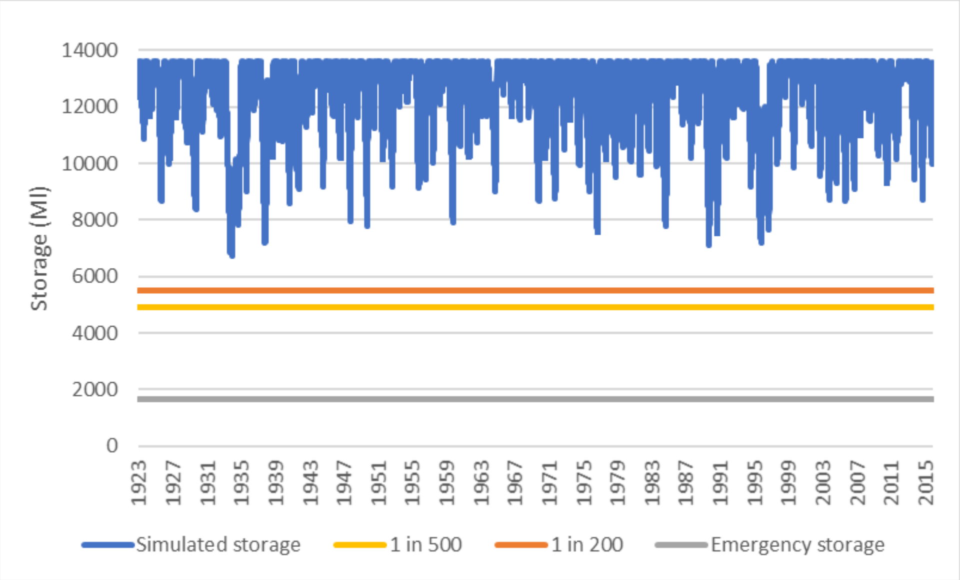


Figure 4-21 - Alwen reservoir extreme value analysis results (baseline)

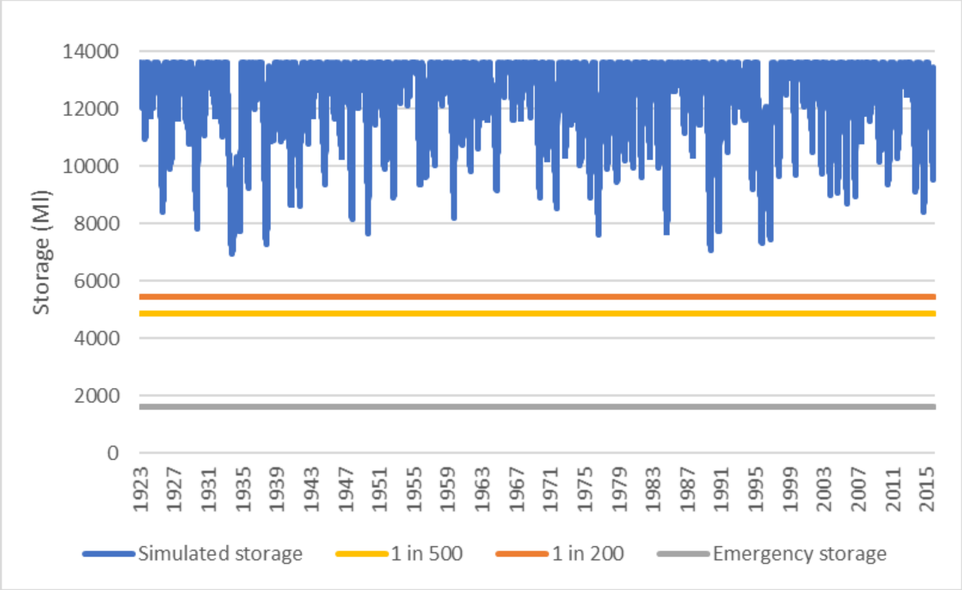


Figure 4-22 - Alwen reservoir extreme value analysis results (2030s)

Table 4-4 - Extreme Value Analysis return period versus storage

Return Period	Probability	Baseline storage (Ml)	Climate change storage (Ml)
500	0.0020	4900	4850
200	0.0050	5500	5460

4.4. Tywyn Aberdyfi

This water resource zone covers the small coastal area around the towns of Tywyn and Aberdyfi in Mid Wales. There are approximately 4,700 customers in this zone but the demand can increase significantly during the summer due to tourism.

Penybont is the only water treatment works in the zone. It is fed from two small river abstractions; the Afon Fathew and the Nant Braich-y-Rhiw. The Nant Braich-y-Rhiw abstraction licence has a condition which prevents use of the source when the river levels are low. This comes into operation during most summer periods; at which point DCWW becomes wholly reliant upon the Afon Fathew.

There is a forecast supply-demand deficit in this WRZ and the WRMP19 preferred plan includes a new river abstraction from the Afon Dysynni. As this is a much larger catchment it removes any plausible drought risk. A new 8 Ml bankside storage reservoir may also form part of the overall AMP7 scheme. This will provide additional drought resilience but also resilience to other potential hazards such as water quality.

Therefore, the key focus of the assessment undertaken here is the baseline position as the planned new abstraction from the Afon Dysynni is known to remove any plausible drought risk..

4.4.1. Key Modelling Assumptions

As there is currently no storage in the Tywyn Aberdyfi WRZ, the drought risk analysis comprised a daily comparison between demand and available flow in the river. The risk under each level of drought severity was calculated as the expected number of days where the river flow is lower than demand. Table 4-5 below presents the key assumptions used for the DVF analysis

Table 4-5 - Summary of Key Modelling Assumptions

Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	2.0 Ml/d DYCP	The demand profile that has been used is based on WRAPSim, with a peak week demand of 1.7Ml/d, this was scaled so that the peak week equalled 2Ml/d when the drought vulnerability assessment was carried out. 2Ml/d = DI plus Target Headroom *excluding climate change* plus process losses plus outage (2020/21).
Durations Analysed	3, 6, 12, 18 months	Small catchment with limited baseflow; analysis is focused on low flow durations
Months Ending Analysed	August, September	Lowest flow periods according to historic data
Failure Criterion	Duration where flows<demand	See above
Climate Change Scenario Used	Weighted average	Weighted average for all 2030 scenarios, as per the HR Wallingford report

4.4.2. Methodology: Baseline

DVF method 1b – full stochastics using direct flow generation was selected as the analysis method for the WRZ. The methodology that was used was selected for two key reasons:

1. The WRZ is potentially at risk from drought, and the studies carried out for WRMP19 showed that the risk is related to flows in a single river (Afon Fathew). The supply from the second source (Nant Braich-Y-Rhyw) reduces to zero under any significant drought event as the Hands off Flow abstraction licence condition takes effect. The risk and duration of failure is therefore dependent on the timing of peak demands against low river flows; therefore, greater confidence is required over both the duration and timing of these events.
2. There is some uncertainty in the hydrology used for WRMP19 as the modelled river flows are based on the nearby Afon Leri gauge. The selected method allows a combination of flow modelling and extreme value analysis to be used to provide confidence in the result. This would not be the case if weather generation and rainfall-runoff modelling had been used, as the capability of the model to extrapolate to severe events may be highly vulnerable to the parameterisation of the hydrological model itself. The method selected therefore allowed the analysis to be based on the flows generated within the range of historic droughts.

A summary of the exact method used is provided in Figure 4-23 below.

1. Calculate rainfall deficit/total flow relationships for all scenarios* using the historic record.

2. Generate a stochastic monthly average timeseries for the WRAPSim Fathew downstream gauge (10,000 years) using the PARMA functionality within the SAMS modelling package. Adjust low flows according to historic EVA. For each stochastic year, assign a nominal rainfall deficit for each scenario based on the stage 1 analysis.

3. Generate daily flows based on re-sampling of the historic record

4. Check the tails of both the monthly average and monthly minimum flow probability curves generated in SAMs against an Extreme Value analysis of each summer & autumn month (July to October inclusive) and modify as appropriate. Use the combination of SAMs month to month timeseries and the EVA to generate a plausible daily flow record for the severe events

5. Compare the daily flows for each year against the demand profile to determine the number of days where flow < demand

6. Plot the DRS based on the number of days failure and the calculated rainfall deficit for each scenario for each stochastically generated year.

Notes:
*'scenarios' refer to the combination of duration and month ending that is being analysed – i.e. each column in the DRS
** 'critical duration' is a concept taken from the DVF and refers to the drought duration where you get the most risk for each return period banding.

Figure 4-23 Summary of the Method Used

Outputs and comments from Stages 1 to 5 are provided below.

Stage 1: Calculation of Rainfall Deficit/Flow Relationships

Because the full stochastic data set could be used (i.e. there was no sampling), a simple relationship was used whereby the percentile ranking of flow and rainfall was the same for each scenario. For example, in the 3 months drought ending August scenario, the stochastic year with the lowest total 3 monthly flow was given a 3 month rainfall deficit equal to a 1 in 10,000 year event. The 100th lowest raking year by flow was assigned a rainfall deficit equal to a 1 in 100 year event, and so on. The only analysis carried out of rainfall was therefore an Extreme Value Analysis for each duration and month ending scenario, using the historic record (taken from the historic catchment data set). Illustrative outputs from that analysis are provided in Figure 4-24 below. As shown, for the 'month ending' August, there was a quite distinct change in slope for the shorter duration events – a 'points over threshold' method based on the lowest 15% of data was therefore applied in this case. This is despite the fact that a longer-term rainfall record was used (the GEAR data set), so it clearly indicates there is a potentially strong summer 'persistence' effect in this area, which tends to end in September. The fact that the two driest events (1976 and 1984) ended fairly abruptly in early September exacerbates the underlying difference. This is reflected in the DRS results shown in Section 4.4.4.

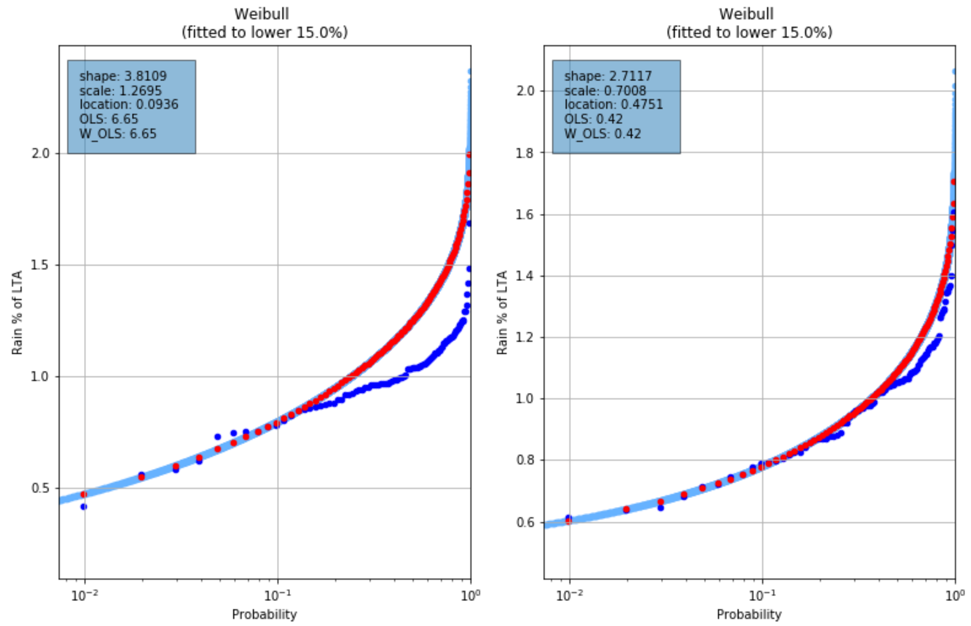
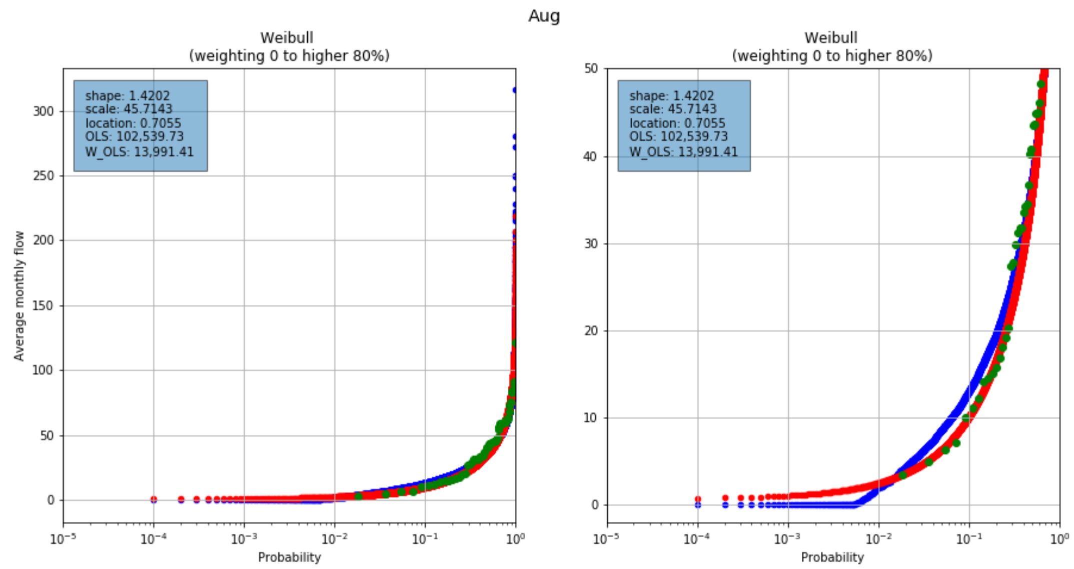


Figure 4-24 Weibull EVA Rainfall fit for 6 Months ending August (left) and September (right)

Stages 2 to 4: Generation of Daily Stochastic Flow Records

The generation of the monthly stochastic flow records was reasonably straightforward and produced a reliable fit. In this case it was necessary to ensure that the extrapolation of flows beyond the probabilities encountered in the historic record was guided using more sophisticated Extreme Value Analysis, as SAMs relies on a transformation process that will tend to over-estimate the risk as flows tend towards zero. Effectively the analysis relied on SAMS to identify the probability of subsequent low flow months, and then finessed the in-month flows based on EVA. The two most critical months of the EVA adjustment process (August and September) are provided in Figure 4-25 and Figure 4-26 below. The analysis relied on a 'points over threshold' approach, applied to the lowest 25% of historic months (the 25% threshold was based on the clear curve 'break' evident in the historic record at this point).



Comparison between basic SAMS output and the EVA (blue line) adjusted fit (red line), calibrated against the historic record (green dots)

Figure 4-25 EVA Flow Adjustment Developed for August

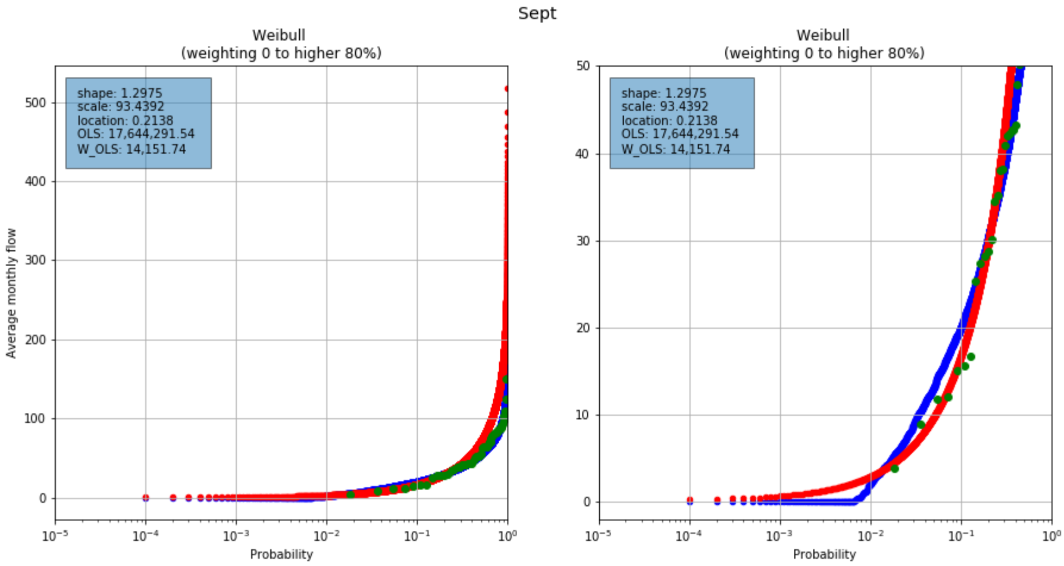


Figure 4-26 EVA Adjustment Developed for September

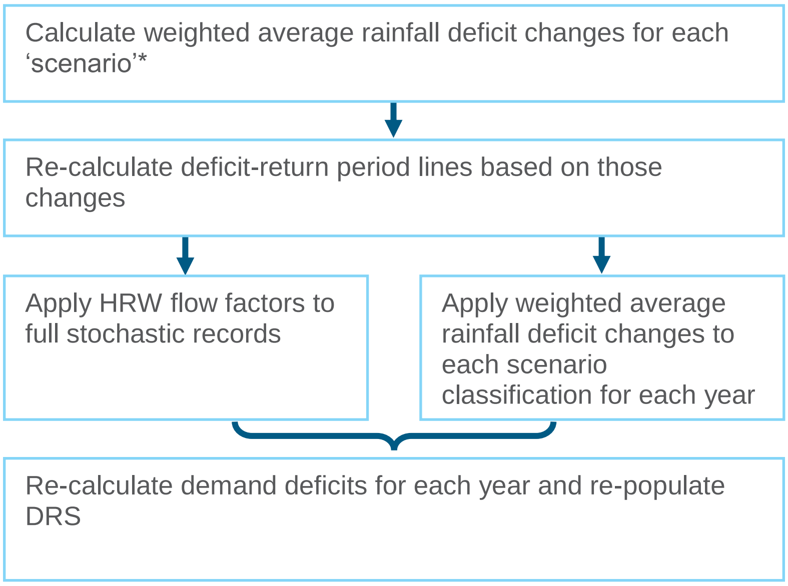
Daily flows were generated through monthly ‘nearest neighbour’ re-sampling of the historic record, which was scaled according to the generated stochastic flow.

Stage 5 Analysis of the Number of Days Failure

The number of days failure in each year for the baseline run was calculated by comparing a repeating demand profile against the generated daily flows in that year. No analysis of the Afon Dysynni scheme was undertaken as the scheme was known to be resilient to plausible droughts (Section 4.4).

4.4.3. Methodology: 2030s Climate Scenario

The impact of climate change on rainfall deficits and flows was undertaken using the general methodology shown in Figure 4-27.



Notes:
** the weighted calculation is used to calculate the percentage rainfall change for each duration and month ending scenario, using the HRW rainfall perturbation factors, and the equation:*

$$\%\ change\ in\ rainfall\ for\ scenario\ x = \frac{\sum_{i=1}^{n}(rain * \%change)_{month\ i}}{\sum_{i=1}^{n}(rain)_{month\ i}}$$

Where scenario x = a given combination of duration and month ending (e.g. 6 months ending August)

Figure 4-27 Climate Change Impact Assessment Method

Flow factors used from the HR Wallingford report are provided below.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Flow Factor (%)	5.62	9.51	3.08	0.64	-4.56	-22.23	-28.32	-32.91	-21.8	-0.21	16.26	14.49

4.4.4. Results

Drought Risk Analysis

Probability-failure plots for the baseline scenario are provided in Figure 4-28 below. This shows that failure starts to occur at around 1 in 40 years, with failure durations increasing to around 25-30 days under a 1 in 200 year event. These return periods are slightly lower (i.e. risk is worse) than the analysis provided for the WRMP19 resilience analysis. This is simply because WRMP19 ran the demand at a level equal to DO (1.7Mld). As the WRZ is in deficit, an analysis based on DI plus Target Headroom plus outage and process losses (2Ml/d) will result in more failures.

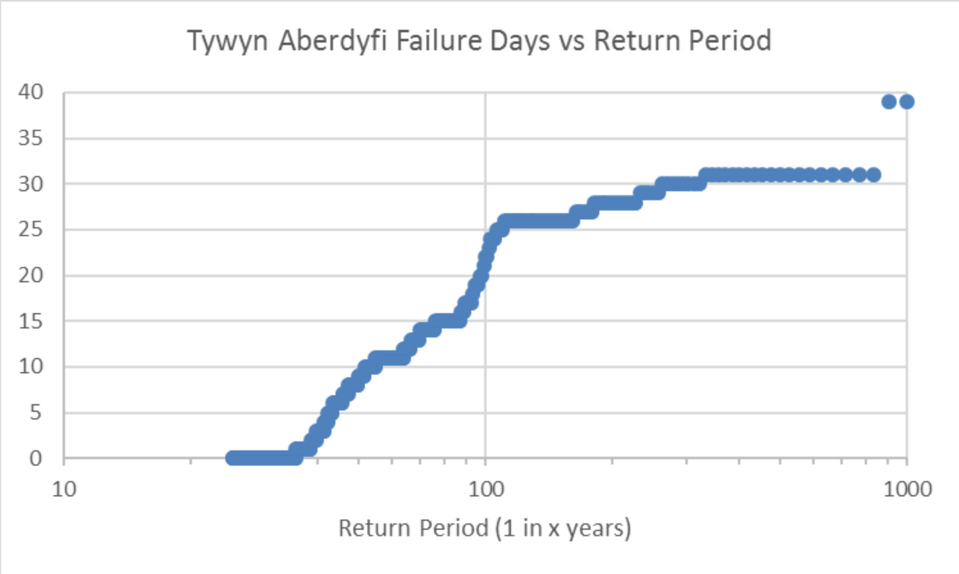


Figure 4-28 Failure Duration versus Probability Analysis for Tywyn Aberdyfi

The same analysis carried out under the 2030s climate change scenario is provided in

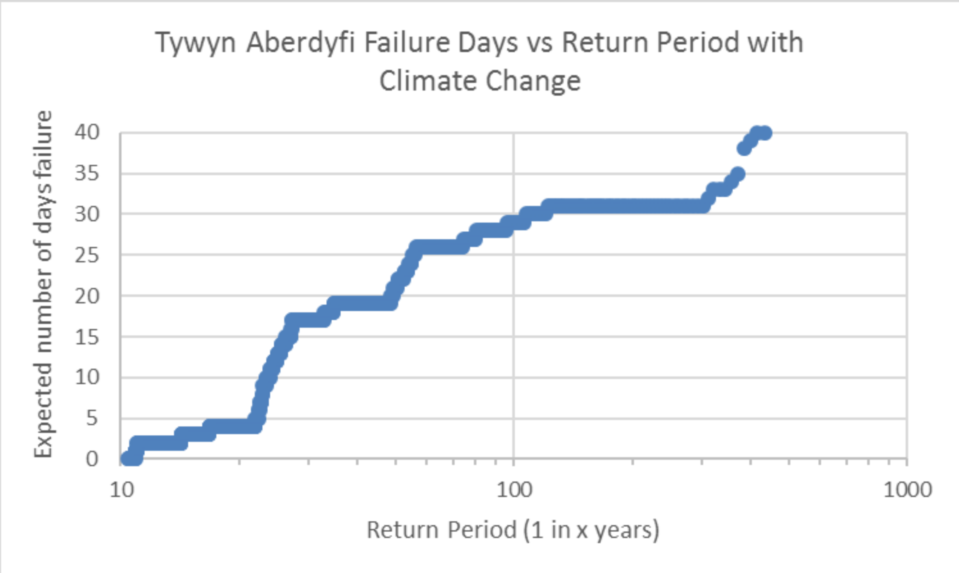


Figure 4-29 below.

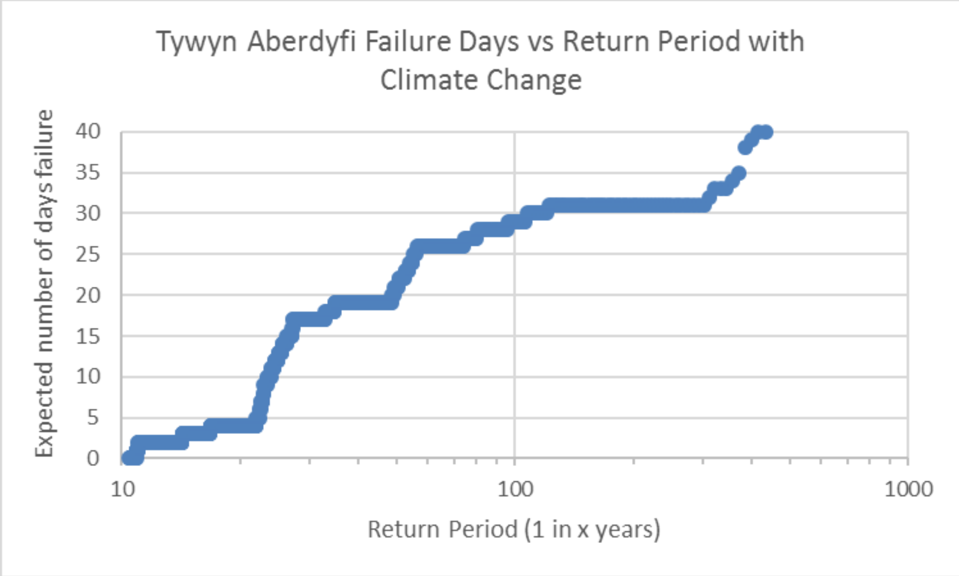


Figure 4-29 Failure Duration versus Probability Analysis for Tywyn Aberdyfi with 2030s climate change

This shows that there is a notable increase in risk, with the chances of failure reducing down to just over 1 in 10 years. Checking back against the historic record, there are three years where minimum flows could drop below the 2Ml/d flow threshold if climate change factors are applied (1976, 1984 and 1959), and one (1995) that would be close to failure. This means a 1 in 15 year failure expectation simply based on the historic record, so the results are plausible

Drought Response Surfaces

The DRS without climate change are provided in Figure 4-30 below. It should be noted that in this case 'failure' represents the expected duration where flows in the Afon Fathew are below the calculated demand level.

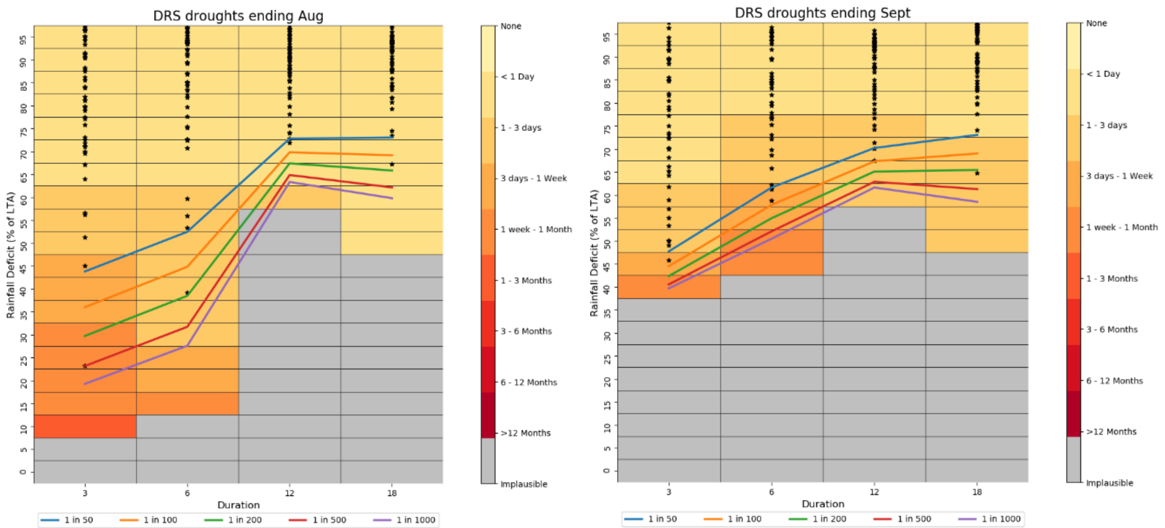


Figure 4-30 Baseline Generated Drought Response Surface

The risk for the WRZ is clearly driven by short duration (3 to 6 month) events. The nature of rainfall in this area also has a strong effect on the DRS, as it has both a relatively high mean monthly rainfall across the summer, but also a high degree of variability. The impact of 'blocking' high pressure systems appears to have a disproportionally high impact over the late spring and summer period. Within the historic record there are three events (1976, 1984 and 1995) where an arid summer period followed a dry spring, and all of these were significantly lower than a simple 5th percentile analysis (i.e. a large amount of deviation under very dry conditions). However, in all three cases the rainfall in September was over 100mm. The lowest four '3 months ending

September' events (1913, 1933, 1959, 2002) in the record all had some relatively normal months during the summer, with only the September in isolation being very dry, so the deviation from a simple percentile analysis was limited.

There is insufficient data even in the GEAR data set to determine how much of this effect is driven by pure chance and how much is associated with the underlying climate, but it is likely some of it is due to chance and hence the rainfall deficits should be smoothed between the two 'month endings' and the 6 -12 -18 month durations to some extent. However, it is also important to note that those events that do extend to September can result in very low flows and greater failure durations due to the longer recession period, even if the apparent deficit is lower. Non-trivial failure risks could occur with a rainfall deficit as little as 25% over 6 months, provided this is concentrated in the July to September period (i.e. 40% deficit over those three months can be a risk if it has been reasonably dry during the spring and early summer).

The DRS with climate change, as show in in Figure 4-31 follows a similar pattern, but the chances of those rainfall deficits occurring increases to the point where failure events could occur frequently and rapidly (even 6 month deficit indicators will start to show failure quite frequently).

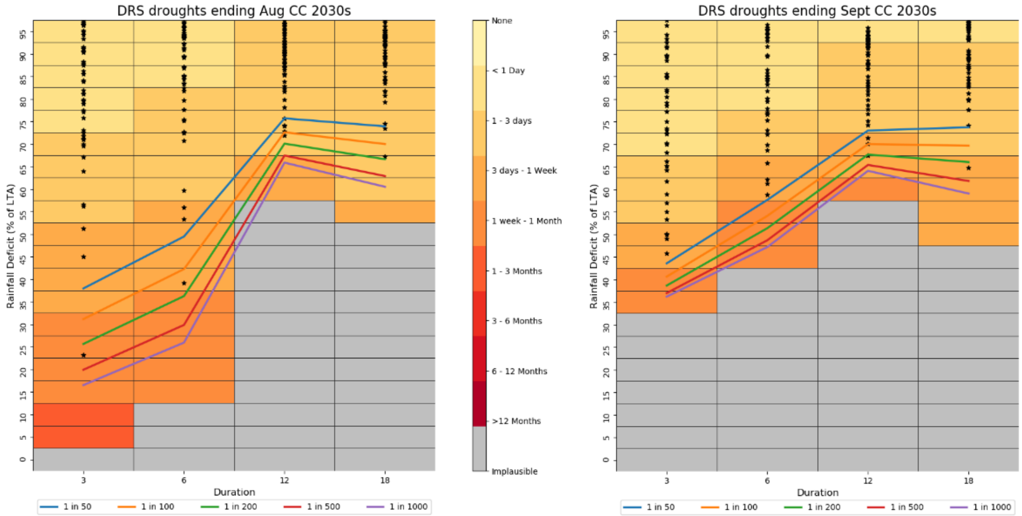


Figure 4-31 Generated Drought Response Surface with 2030s climate

4.5. Blaenau Ffestiniog

Blaenau Ffestiniog is a single-source WRZ with Llyn Morwynion supplying Garreglwyd water treatment works. When the storage in Llyn Morwynion is low, water is transferred from the nearby Afon Gam. The abstraction licence for Llyn Morwynion and Afon Gam has recently been modified due to the outcomes of NRW’s Habitats Directive Review of Consents. Water must be transferred from the Afon Gam if the lake level drops below 157 Ml.

As outlined in Section 2.2, previous resilience assessments using EVA have shown that the Blaenau Ffestiniog WRZ is very resilient. For the DVF, the 1 in 200 and 1 in 500 year minimum storage levels of Morwynion Reservoir were compared against the recent licence condition. As shown in Figure 4-32, these levels are well above the licence condition, hence Llyn Morwynion is very resilient even without accounting for the additional benefits of the transfer from Afon Gam.

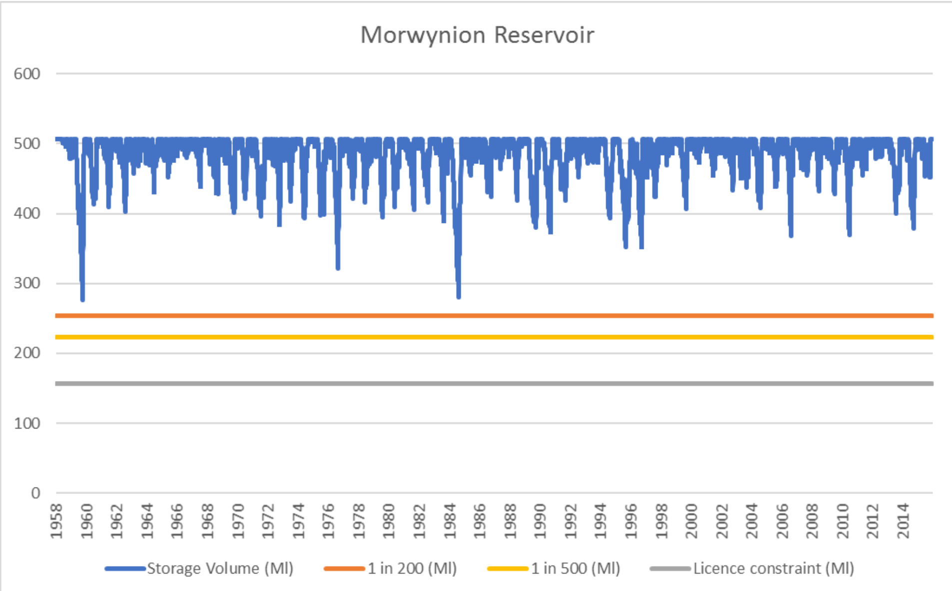


Figure 4-32 - Extreme Value Analysis results for Blaenau Ffestiniog (Morwynion Reservoir) showing new licence condition at 157 Ml

4.6. Barmouth and Lleyn Harlech

4.6.1. Key Modelling Assumptions

During the 2018 dry weather period stocks in Bodlyn (Barmouth WRZ) were becoming a concern as levels entered the developing drought action zone. Water resources in the Lleyn Harlech zone were in a healthier position during this period. Network changes were implemented to allow water from Eiddew Mawr and Tecwyn (via Rhiw Goch and Cilfor WTWs) to be transferred to the Barmouth WRZ to alleviate pressure on Bodlyn and prevent stocks crossing into the drought action zone (DAZ). For the 2020 drought plan it was considered a better representation of operational behaviour to amalgamate both Lleyn Harlech and Barmouth water resource models. This would allow the network changes undertaken in 2018 to be simulated and allow for a better understanding of the level of risk to both zones under more extreme drought scenarios.

Therefore, the WRZs have been assessed here on a combined basis. The new Aquator model combining these WRZ was employed in place of the previous WRAPSim models. This work was undertaken by DCWW staff.

Table 4-6 - Summary of Key Modelling Assumptions

Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	Lleyn Harlech 14.20 Ml/d plus Barmouth 2.09 Ml/d DYAA	This reflects a significant available surplus in the WRZ. The demand value is based on DI, plus Target Headroom, plus outage and process losses. Profile based on Aquator.
Durations Analysed	6, 12, 18, 24 and 48 months	Storage relies on high rainfall in the mountains, so can be vulnerable to quite short duration, but very high intensity, drought events
Months Ending Analysed	September, October	Reflects the occurrence of minimum storage levels in the historic record
Failure Criterion	Emergency storage failure	Failure of emergency storage on aggregate across all reservoirs (emergency storage = 30 days demand)

4.6.2. Methodology: Baseline

Due to the perceived level of drought risk in the WRZ, it was analysed using DVF method 1b (stochastic weather and flow generation). The impacts on yield and system failure needed to be run through Aquator, so a ‘drought library’ approach was taken to sample representative droughts from the full stochastically generated flow and rainfall data set. A summary of the methodology that was adopted for Barmouth and Lleyn Harlech is provided in Figure 4-33.

1. Generate a spatially coherent stochastic rainfall and PET record for all catchments. Generate associated flows using Catchmod

2. Assign each year a rainfall deficit by scenario (based on the average stochastic rainfall for that year). Generate rainfall deficit/probability curves from the stochastically generated data set.

3. Use the lookup matrix to select an appropriate number of drought events in each rainfall deficit/duration for testing in Aquator

4. Generate a drought library timeseries input, based on the selected drought events and the lookup table of warm up and cool down requirements for the different drought durations.

5. Run the 500 year drought library through Aquator. Review results and examine both aggregate failures against emergency storage and individual reservoir responses.

6. Plot the DRS based on the number of days failure and the calculated rainfall deficit for each scenario for each stochastically generated year.

Figure 4-33 - Summary of Analysis Method

Outputs and comments from Stages 1 to 6 are provided below.

Stage 1: Generation of Stochastic Weather and Flows

The process used for stochastic weather generation is the same as that used for Pembrokeshire for WRMP19, full details can therefore be found within the WRMP19 technical appendix. For Barmouth and Lleyn Harlech the existing Hysim models were converted into Catchmod and re-calibrated (see separate Hydrology report[2]).

Stage 2: Generation of Rainfall Deficit/Probability Curves

As the stochastically generated weather set contained over 12,000 years of record, the deficit/probability curves were created by inverse ranking of the generated rainfall data set.

Stages 3 and 4: Generation of the Drought Library

Barmouth and Lleyn Harlech were assessed as higher risk WRZs and so each drought library that was run through the Aquator model consisted of approximately 500 years' worth of generated data. This drought library was sampled from the full stochastic data set based on the matrix shown in Table 3-2.

The number of droughts involved was purely a pragmatic decision that balanced the need to fully explore the drought risk in each DRS cell against the run times involved in Aquator. As shown, all events up to 1 in 1000 years return period had at least 4 droughts explored for each combination of rainfall severity and duration, which should be sufficient to identify if there is a significant risk for that type of drought.

Stages 5 and 6: Generation of Failure Data and the Final DRS

The drought libraries were run through Aquator and the volumetric responses in each reservoir at the selected level of demand (Table 4-6) was recorded. These responses were then examined in a post processing stage to assess the duration of emergency storage failures for each drought event.

4.6.3. Catchmod modelling

Catchmod models were developed in place of the previous Hysim models due to the need to simulate long stochastic rainfall records. This work is described in the separate hydrology report[2].

4.6.4. Results

The Lleyn Harlech DAZs are derived from the combined storage of Cwmystradllyn and Tecwyn Uchaf. Stocks in Cwm Dulyn and Eiddew Mawr aren't considered for the DAZs as their supply areas can be rezoned so that demand can be met by Cwmystradllyn and Tecwyn Uchaf respectively. Stocks in Cwm Dulyn and Eiddew Mawr are however important to provide support to the NEYM (Section 4.1) and Barmouth zones respectively. There is considerable uncertainty regarding the hydrology of Eiddew Mawr as the observed data suggests there is a loss from the lake of ~1 Ml/d. This may be due to it being a natural lake with no proper impoundment, allowing water to leak through the broken crest. DCWW has no data to quantify what the loss may be when the lake is drawn down (when a lower rate of loss would be expected due to a reduced hydraulic head). Therefore, in the DCWW Aquator simulation of the stochastic drought library, two different scenarios were tested in the combined Lleyn Harlech – Barmouth model; one with no loss at Eiddew Mawr (best case) and one with a continuous 1 Ml/d loss (worst case). These two scenarios determine the level of support that can be provided from the Lleyn Harlech zone to the Barmouth zone.

Both scenarios had no emergency storage failures at any reservoirs under a 1 in 200 drought. The 1 Ml/d loss scenario however results in small demand shortfalls in the Barmouth & Harlech demand zones as Eiddew Mawr reaches the level at which we can no longer abstract according to the new Habitats Directive licence. These demand shortfalls occur for short periods during peak summer demand where there is insufficient yield at Tecwyn and Bodlyn to compensate for the loss of supply from Eiddew Mawr. Tankering of small volumes of treated water may be required to avoid these demand shortfalls depending on the levels of losses seen from Eiddew Mawr when the lake is low.

Although reservoir levels will fall lower than they have in the past under these more severe drought scenarios, the Aquator analysis shows there will be enough resource within the zone as a whole to avoid the need for extreme supply side measures.

4.7. Tywi CUS

4.7.1. Key Modelling Assumptions

The Tywi Gower Conjunctive Use System (CUS) is a large WRZ whose water supply is from a combination of four impounding reservoirs and two river abstractions, which are operated conjunctively to generate the yield. Due to the relatively complex nature of the water resource arrangement it was necessary to carry out flow generation as part of the drought vulnerability assessment. However, the low risk nature of the WRZ meant this could be done using one of the simpler DVF assessment methods. Table 4-7 below presents the key assumptions used for the DVF analysis

Table 4-7 - Summary of Key Modelling Assumptions

Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	187.4 Ml/d DYAA (plus 12 Ml/d export to SEWCUS)	Based on DI, plus Target Headroom, plus outage and process losses. Profile based on WRAPsim.
Durations Analysed	6, 12, 18, 24 and 48 months	
Months Ending Analysed	September, October	Lowest flow periods according to historic data – some uncertainty over individual reservoir responses so three months ending tested in this case
Failure Criterion	Duration where storage is below emergency	Failure of emergency storage (emergency storage = 30 days demand (supply plus compensation water))

Parameter	Value(s) Used	Comments/Notes
Climate Change Scenario Used		Future flow scenario FF-HadRM3-Q16_afixq

4.7.2. Methodology: Baseline

Tywi CUS is a lower risk WRZ so method 4a was adopted – i.e. re-sampling and scaling of the historic flow record. A summary of the methodology utilised for the Tywi zone is provided in Figure 4-34 below.

1. Calculate rainfall deficit/total flow relationships for all scenarios using the historic record.
2. Generate a stochastic monthly average timeseries across all of the WRAPSim input catchments. For each stochastic year, assign a nominal rainfall deficit for each scenario based on the historical relationship.
3. Use the lookup matrix to select an appropriate number of drought events in each rainfall deficit/duration for testing in WRAPSim
4. Generate a drought library timeseries input, based on the selected drought events and the lookup table of warm up and cool down requirements for the different drought durations.
5. Run the 500 year drought library through WRAPSim. Review results and examine both aggregate 'Big 5' failures against emergency storage and individual reservoir responses.
6. Plot the DRS based on the number of days failure and the calculated rainfall deficit for each scenario for each stochastically generated year.

Figure 4-34 - Summary of Analysis Method

Outputs and comments from Stages 1 to 4 are provided below.

Stage 1: Extreme Value Analysis (EVA) of Rainfall Deficit

Rainfall deficit probabilities for each scenario were generated using the historic record and EVA curve fitting. The process was relatively straightforward and example outputs from that analysis are provided in Figure 4-35.

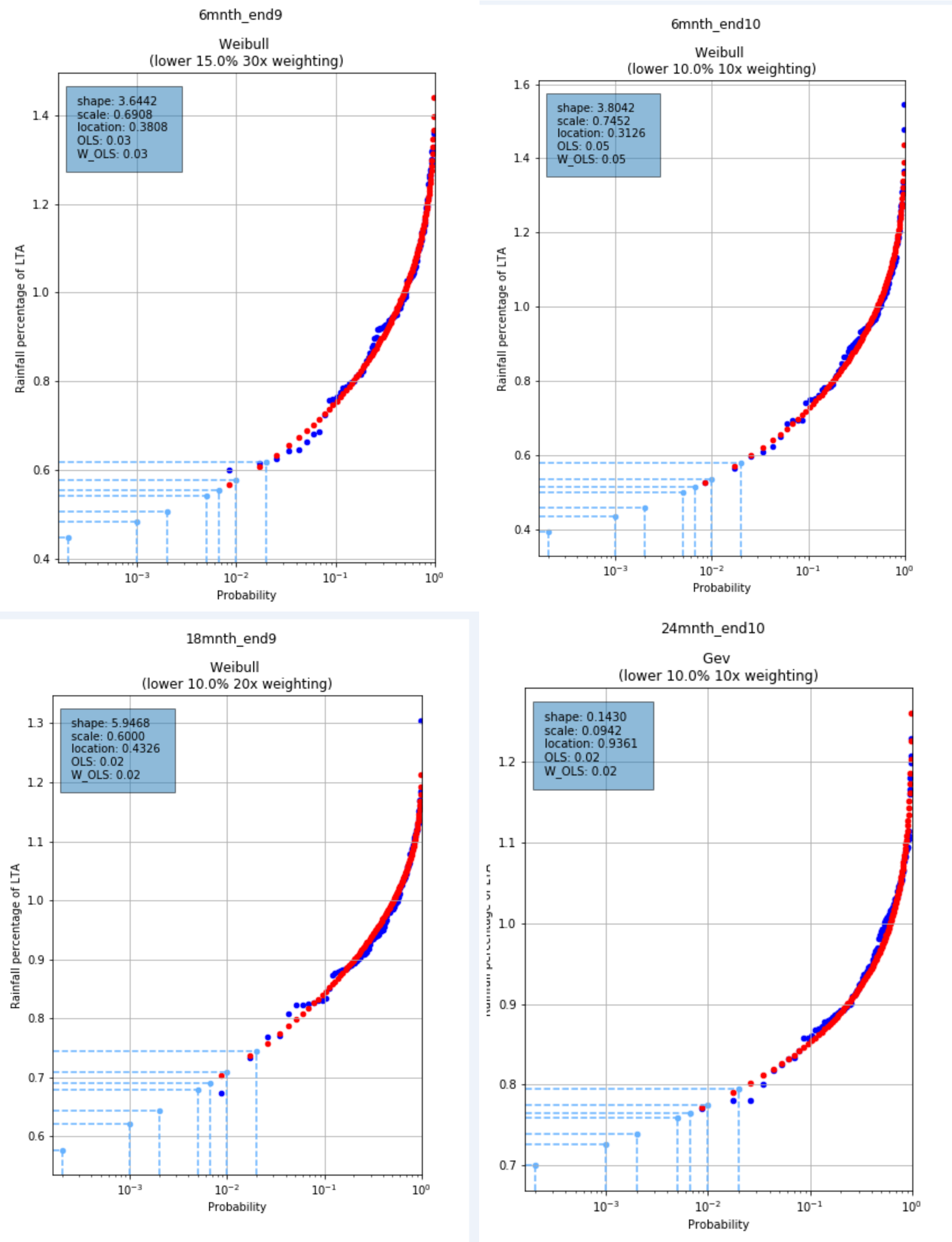


Figure 4-35 - Example EVA Plots for Tywi CUS

Stage 2: Calculation of Rainfall Deficit/Flow Relationships

The generation of flows followed the DVF method 4a, whereby flows are generated from the historic record based on regression analysis between cumulative flows and rainfall, which are then used to scale the historic record for specific droughts. Because of the flashy nature of the catchments the correlation between cumulative flows and rainfall was relatively poor in some cases, so it was necessary to ensure that the uncertainty range around the correlation could be sampled to provide a representative range of droughts for each given rainfall deficits. Therefore, both the correlation and the uncertainty range were analysed and defined, to enable the selection process described in Section 4. Examples of the outputs from this analysis are provided below in Figure 4-36.

These figures show how the cumulative flow over the defined drought duration and end month (e.g. 6 months ending September) correlate with the rainfall deficits over that time period. The red banding shows the 25th and 75th percentile uncertainty range from that correlation.

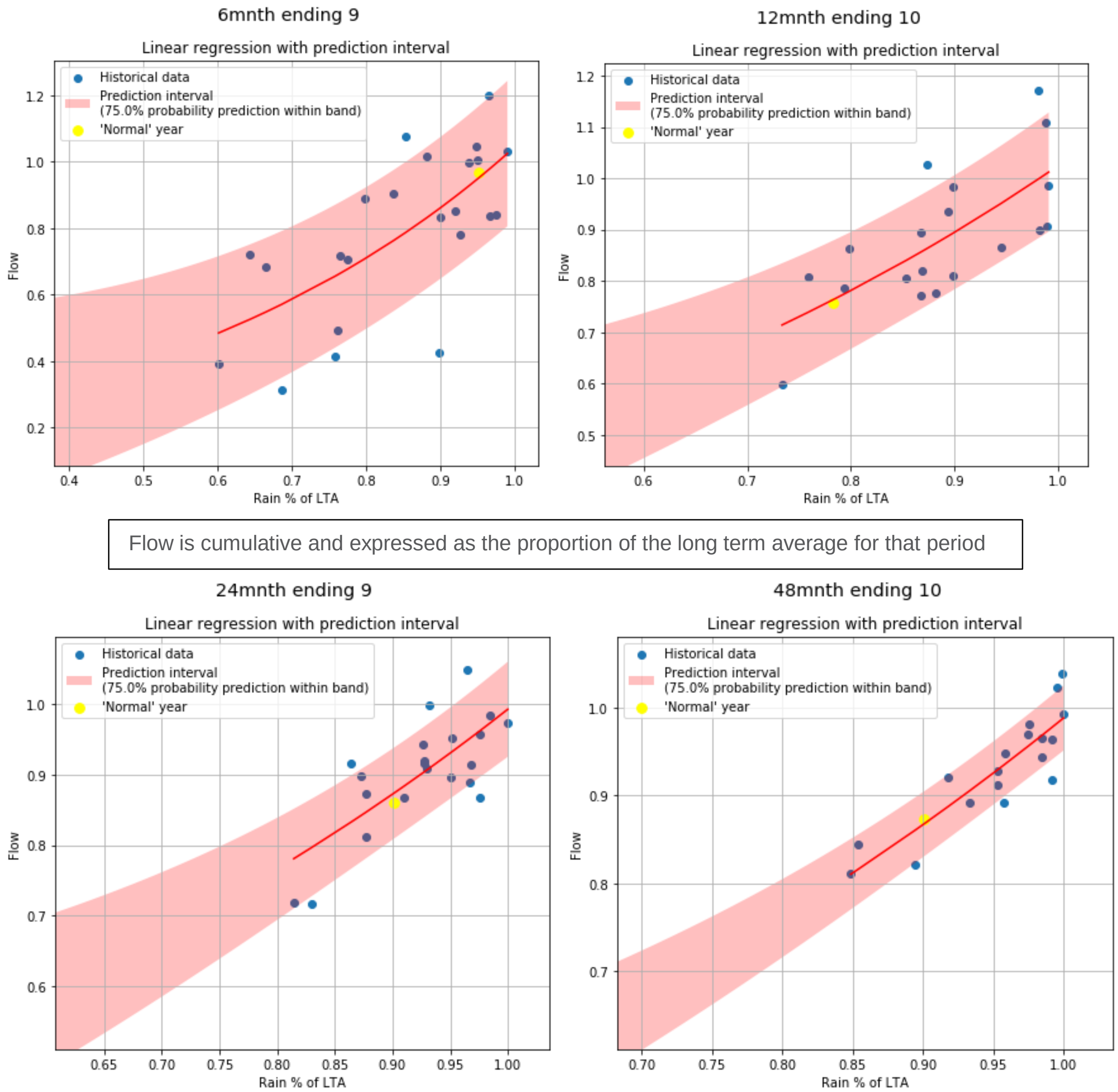


Figure 4-36 - Example Cumulative Flow versus Rainfall Correlation Plots

Stage 3: Selection of Drought Scenarios

As the WRZ was assessed as a lower risk, each drought library that was run through the Tywi model consisted of approximately 200 years' worth of generated data. The number and severity of droughts included in this drought library was based on the matrix shown below in Table 4-8.

Table 4-8 - Severity and duration of events in drought library

Matrix Part 1 - Number of Droughts Selected for Each DRS Cell

Rainfall Deficit Return Period Band (1 in X years)	Drought Duration				
	6m	12m	18m	24m	48m
100	2	2	2	1	1
200	2	4	4	2	2
500	2	3	3	1	1
1000	1	2	2	1	2
5000	1	1	1	1	1

Matrix Part 2 - Guidance on Timeseries Extraction for Each Drought

Drought duration	6m	12m	18m	24m	48m
Years warm up	2	2	2	2	1
years cooldown	1	1	1	1	1
Duration of each event (years)	4	5	5	6	7
Total years in band	32	60	60	36	49
Total years in Drought Library	237				

The number of droughts involved was purely a pragmatic decision that balanced the need to fully explore the drought risk in each cell against the run times involved in WRAPsim. As shown, the analysis was able to generate a number of droughts for the shorter duration events that are likely to be the most challenging for the WRZ.

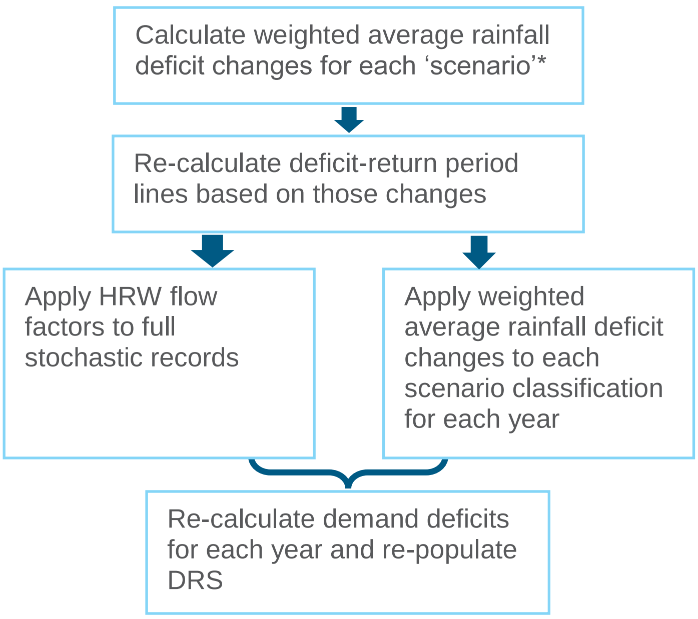
Stage 4: Generation of Flows for the Drought Library

Flows for each drought library were generated based on scaling of the relevant duration from a ‘typical’ year taken from the historic record. The ‘typical’ year was selected as one that was relatively dry, but plotted close to the flow/rainfall/regression line. Examples of this type of year are provided in Figure 4-36, shown on the plot as yellow dots. The difference in rainfall deficit between the ‘typical’ year and the scenario that was being analysed was calculated and this difference was applied to the flow/rainfall deficit algorithm using the following process:

- The difference in rainfall between this ‘typical’ dry year and the drought sequence being generated was calculated.
- The correlation equation between rainfall and flow was used to calculate the flow factor that was relevant to the difference in rainfall. Where there was only a single drought being selected for a deficit/duration band, then this was based on the mean (expected value) of the rainfall/flow regression. Where more than one drought was being analysed for a given deficit/duration cell, then the ratio required to generate a flow equivalent to the 25th percentile (i.e. the lower end of the red band in the Figure 4-36 examples) were also generated. Where there were three or more then the upper 75th percentile was also selected to provide statistical balance across the deficit/duration cell (and hence the DRS as a whole).
- The calculated flow factors were applied to the ‘typical’ historic year for the drought duration to create the flows for that drought sequence.

4.7.3. Methodology: 2030s Climate

The impact of climate change on rainfall deficits and flows was carried out using the general methodology shown in Figure 4-37.



** the weighted calculation is used to calculate the percentage rainfall change for each duration and month ending scenario, using the HRW rainfall perturbation factors, and the equation:*

$$\%\, change\ in\ rainfall\ for\ scenario\ x = \frac{\sum_{i=1}^{n}(rain * \%change)_{month\ i}}{\sum_{i=1}^{n}(rain)_{month\ i}}$$

Where scenario x = a given combination of duration and month ending (e.g. 6 months ending August)

Figure 4-37 - Climate Change Attribution Method

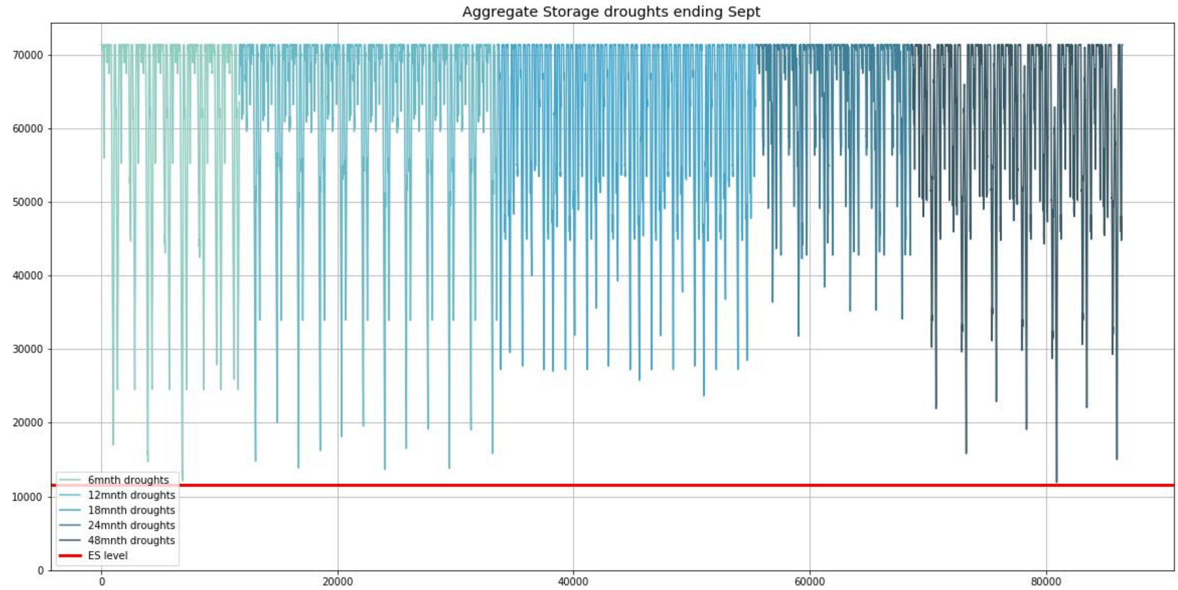
As WRMP19 used Future Flow scenarios for this WRZ it was necessary to use the Future Flow dataset and extract Available Precipitation (incorporating delays due to water storage as snow and ice) at the four grid locations corresponding to the GEAR rainfall data. The change factors were calculated from the difference in the monthly average available precipitation between the baseline (1961-1990) and the 2030's period (2020-2049). These factors were then used to calculate the weighted average change for each duration/ending period as per the other WRZs.

4.7.4. Results

Drought Risk Analysis

This WRZ showed potential vulnerability to different types of events. Under very intense, summer focused events (as represented by the selected 6 month drought patterns), the storage was drawn down to low levels as a result of demand plus the release requirements on the reservoirs. Under longer duration events there is also a risk that the reservoirs will not refill and some risk is posed from 12 month and two year duration events.

The plots below show failures in events of all three of these durations, but failures in the 6 month duration are more prominent. Generally, the impacts of climate are relatively minor, as per the WRMP19 assessment, although they do lead to the only failure at a two year duration. The vast majority of the aggregate storage corresponds to Llyn Brianne; Figure 4-40 shows the simulated combined storage for all reservoirs under the baseline scenario for droughts ending in September. The graph shows that this reservoir is reflective of the aggregate storage with failures for 6 month and two year duration events.



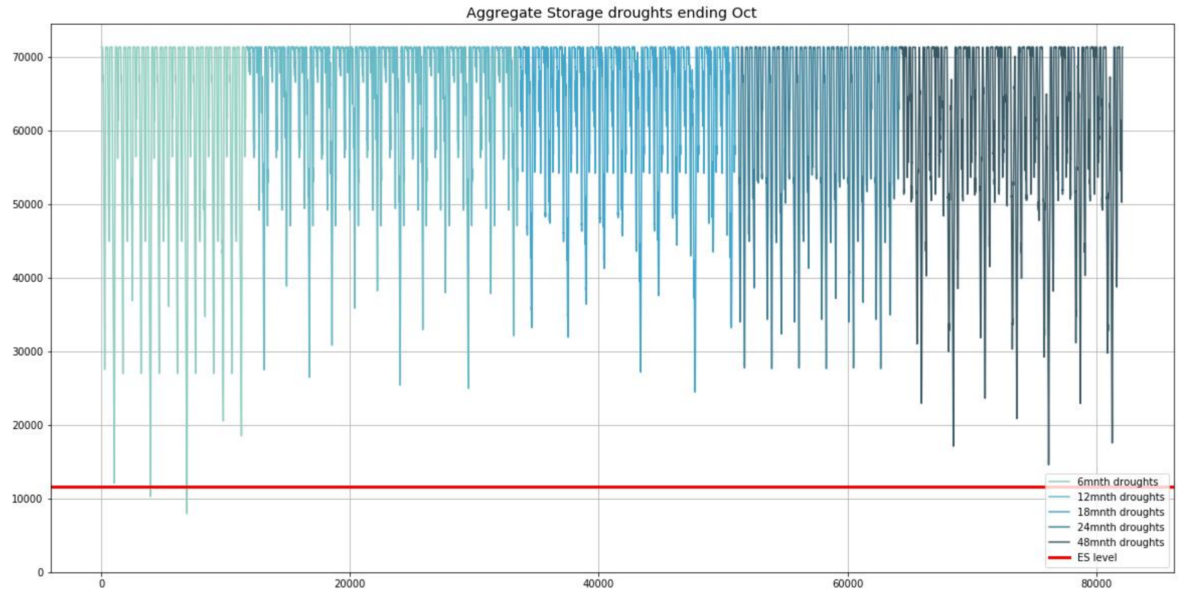


Figure 4-38 - Aggregate Storage Plots for baseline scenario

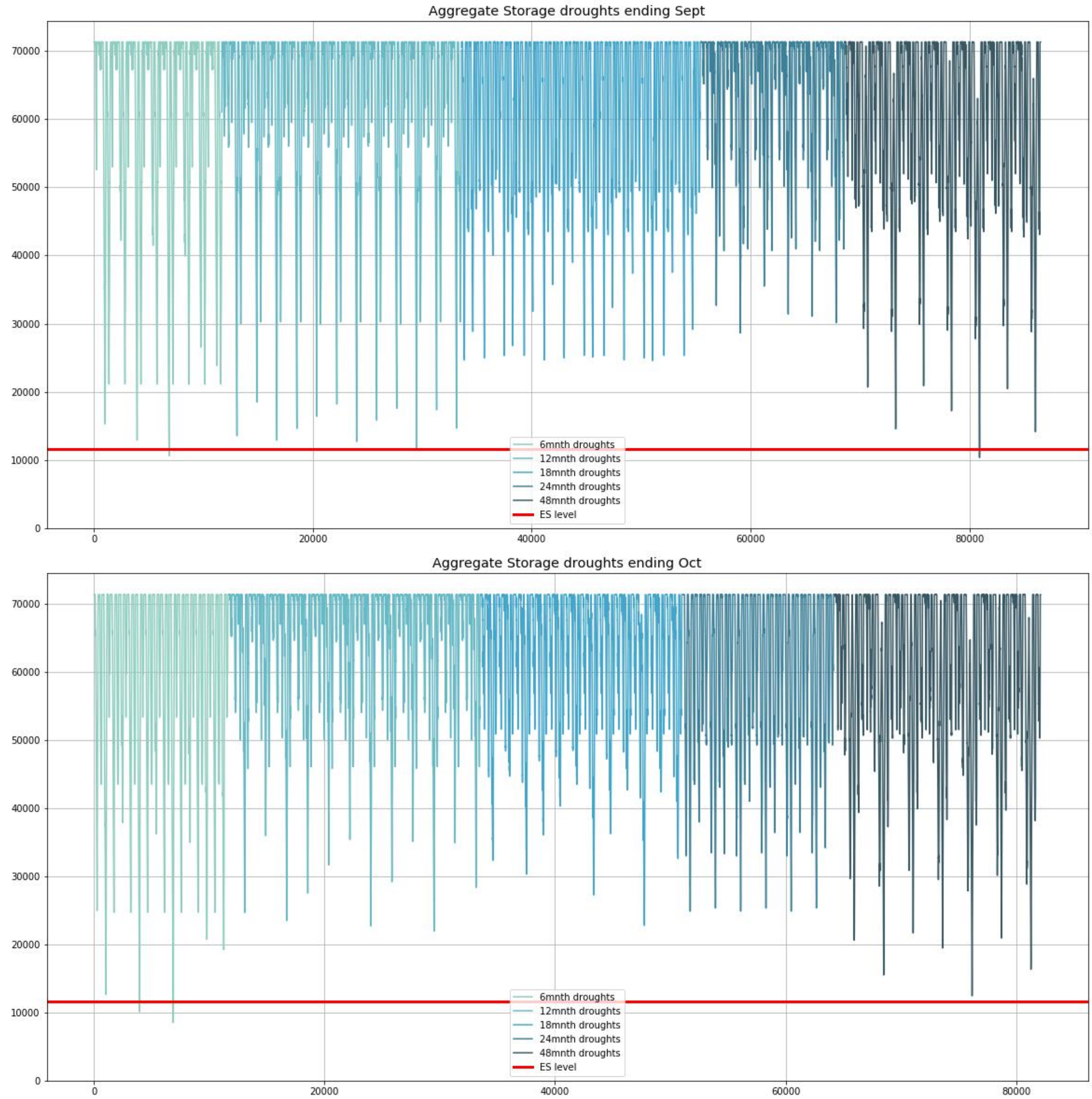


Figure 4-39 - Aggregate Storage Plots for 2030s Climate change scenario

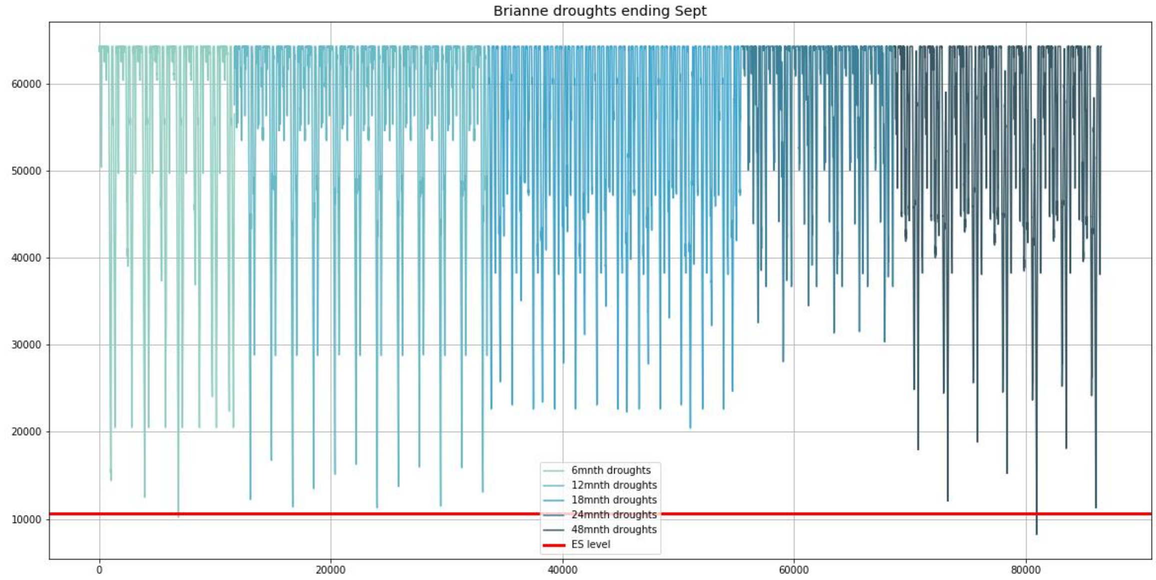


Figure 4-40 – Llyn Brianne Storage Plots for baseline scenario

Drought Response Surfaces

The DRS, as shown in the figures below, are reflective of the aggregate storage plots shown in the previous section. The key risk is 6 month duration events ending in October. For these type of events, climate change actually lessens the impact slightly (climate change inflow perturbations can be positive, as well as negative). In droughts ending September, however, the effects of climate change lead to a higher impact; there are no failures in the baseline scenario for droughts ending September. As noted in the previous section the effects of climate change overall are relatively minor.

The 2 year duration month ending September failure shown in Figure 4-39 does not appear in the corresponding DRS (Figure 4-42). This is due to the fact that the failure occurs just outside of the specified drought window (i.e. later than September) and therefore is not registered in the DRS.

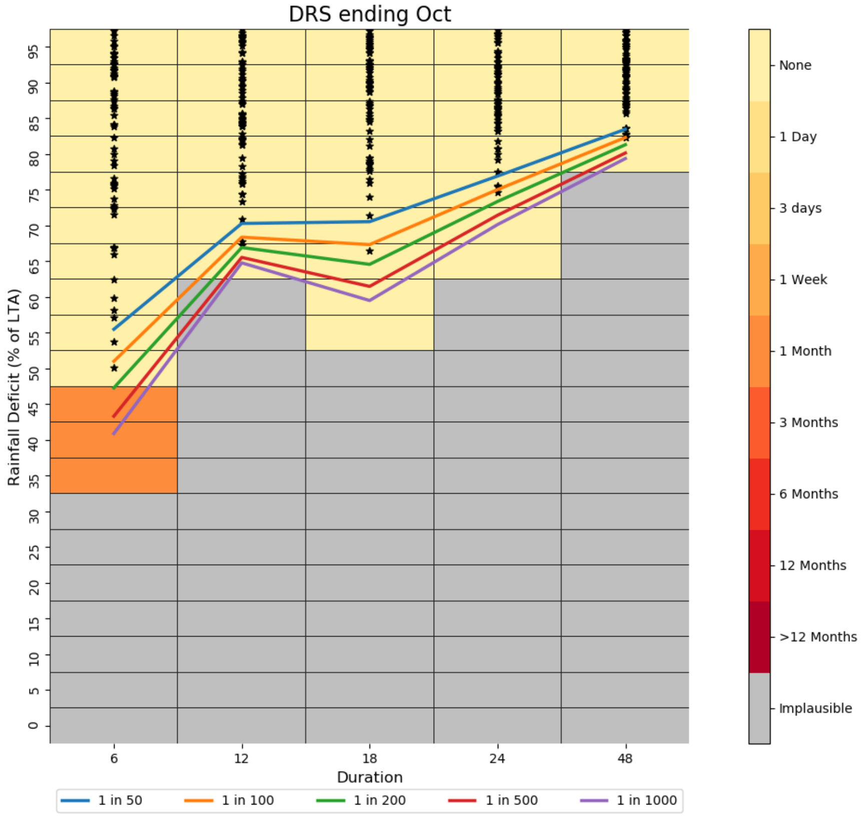


Figure 4-41 Baseline Generated Drought Response Surface (droughts ending October)

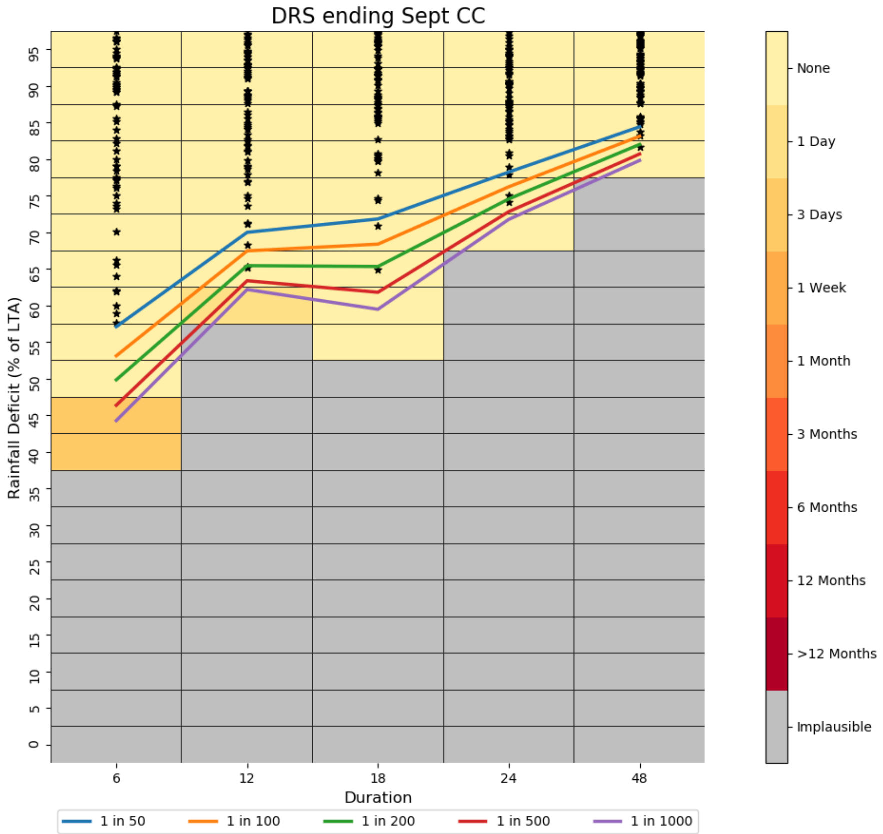


Figure 4-42 Generated Drought Response Surface with 2030s climate (droughts ending September)

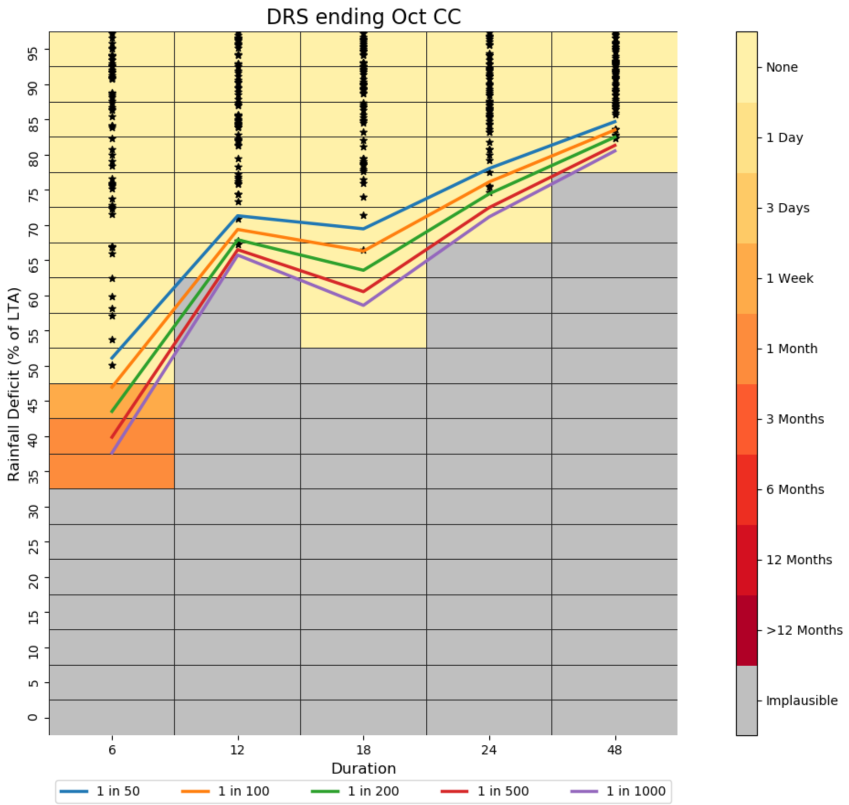


Figure 4-43 Generated Drought Response Surface with 2030s climate (droughts ending October)

4.8. Mid & South Ceredigion

As noted in Section 2.2, DRS were deemed unlikely to be required in this WRZ. The WRMP19 resilience testing showed that, even when demand was set to equal DO, it was unlikely that there would be any deficit unless extremely high drought return periods were tested. Available headroom is over three times Target Headroom throughout the WRMP19 planning period.

As part of this project the hydrology of the WRZ was reviewed with the intention of making improvements if possible. This work is reported separately[2] but involved the development of new Catchmod rainfall-runoff models for the Afon Teifi at Llechryd and Teifi Pools. The representation of the transfer from Pond-Y-Gwaith to Llyn Teifi was also improved.

When the new inflow timeseries were loaded into the WRAPSim model this led to reduced reservoir drawdown in Teifi Pools, i.e. it suggested an even higher level of resilience. As the reduction in drawdown was fairly significant it was not possible, within the timescales of this project, to gain sufficient confidence in the revised hydrology to allow the original resilience assessment to be updated. Therefore, further review of the hydrology has been scheduled, and the WRMP19 position on WRZ resilience is unchanged.

4.9. Pembrokeshire

4.9.1. Key Modelling Assumptions

Pembrokeshire is a relatively complex WRZ, with much of the DO capability depending on the availability of water from the direct river abstraction at Canaston. The abstraction is supported by regulation releases from Llys-y-Fran reservoir and it is this storage that acts as the primary indicator of drought stress and hence 'failure' for the WRZ. The overall DVF analysis considers the WRZ storage between Llys y Fran and Rosebush reservoirs as being conjunctive and hence 'failure' is defined where the reservoirs fall below an aggregated emergency storage value.

WRMP19 identified a supply demand imbalance caused by the inefficiency of the regulation release and abstraction arrangements between Llys-Y-Fran and Canaston. A scheme is therefore planned for delivery in AMP7 to improve the flexibility of pumping at Canaston. This means that there are two setups that were tested in the DVF:

1. The current arrangement, contained within WRAPSim model '5N', which has the less efficient fixed speed pumping arrangements.
2. The proposed new scheme arrangements, contained within WRAPSim model '5M', which incorporates the variable speed, flexible 'put and take' arrangements.

Table 4-9 below presents the key assumptions used for the DVF analysis.

Table 4-9 - Summary of Key Modelling Assumptions

Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	43.00 Ml/d DYAA	The demand value is based on DI, plus Target Headroom, plus outage and process losses. Demand profile based on WRAPSim. WRAPSim includes the additional 28.33Ml/d export to industrial users
Durations Analysed	6, 12, 18, 24 months	The storage is relatively small in comparison to demand, and the river does not have a high baseflow index. Drought risk will therefore occur over two years or less.
Months Ending Analysed	September, October	Reflects the occurrence of minimum storage levels at the same time as minimum flows in the river
Failure Criterion	Duration of storage 'failure'	Failure of emergency storage on aggregate across the two reservoirs (emergency storage = 30 days demand)
Climate Change Scenario Used	5n: UKCPO9_9259 5m: UKCP09_9610	Different scenarios represent the mid-point expectations for the two system set-ups.

4.9.2. Methodology: Baseline

Due to the perceived level of drought risk in the WRZ, it was analysed using DVF method 1a (stochastic weather and flow generation). The impacts on yield and system failure needed to be run through WRAPSim, so a 'drought library' approach was required to sample representative droughts from the full stochastically generated flow and rainfall data set.

A summary of the methodology that was adopted for Pembrokeshire is provided in Figure 4-44 below.

1. Generate a spatially coherent stochastic rainfall and PET record for all catchments. Generate associated flows using Hysim

2. Assign each year a rainfall deficit by scenario (based on the average stochastic rainfall for that year). Generate rainfall deficit/probability curves from the stochastically generated data set.

3. Use the lookup matrix to select an appropriate number of drought events in each rainfall deficit/duration for testing in WRAPSim.

4. Generate a drought library timeseries input, based on the selected drought events and the lookup table of warm up and cool down requirements for the different drought durations.

5. Run the 500 year drought library through WRAPSim. Review results and examine both aggregate failures against emergency storage and individual reservoir responses.

6. Plot the DRS based on the number of days failure and the calculated rainfall deficit for each scenario for each stochastically generated year.

Figure 4-44 - Summary of Analysis Method

Outputs and comments from Stages 1 to 6 are provided below.

Stage 1: Generation of Stochastic Weather and Flows

The stochastic weather generation is the same as that used for WRMP19. Details can therefore be found within the WRMP19 technical appendix. The flows had already been generated for the full stochastic data set using Hysim.

Stage 2: Generation of Rainfall Deficit/Probability Curves

As the stochastically generated weather contained over 12,000 years of data, the deficit/probability curves were created by inverse ranking of the rainfall data set.

Stages 3 and 4: Generation of the Drought Library

As this was assessed as a higher risk WRZ, each drought library that was run through the Pembrokeshire WRAPSim model consisted of approximately 500 years' worth of generated data. This drought library was sampled from the full stochastic data set based on the matrix shown in Table 3-2.

The number of droughts involved was purely a pragmatic decision that balanced the need to fully explore the drought risk in each cell against the run times involved in WRAPSim. As shown, all events up to 1 in 1000 years had at least 4 droughts explored for each combination of rainfall severity and duration, which should be sufficient to identify if there is a significant risk for that type of drought.

Stages 5 and 6: Generation of Failure Data and the Final DRS

These steps were conceptually straightforward. The drought libraries were run through WRAPSim and the volumetric responses in each reservoir at the selected level of demand was recorded. These responses were then examined in a post processing stage to assess the duration of emergency storage breaches for each drought event.

4.9.3. Methodology: 2030s Climate

The impact of climate change on rainfall deficits and flows was carried out using the general methodology shown in Figure 4-45. As the flows were generated from the baseline stochastic weather data set, the impact of climate change on flows and hence the drought library could be calculated directly through perturbation of rainfall and PET.

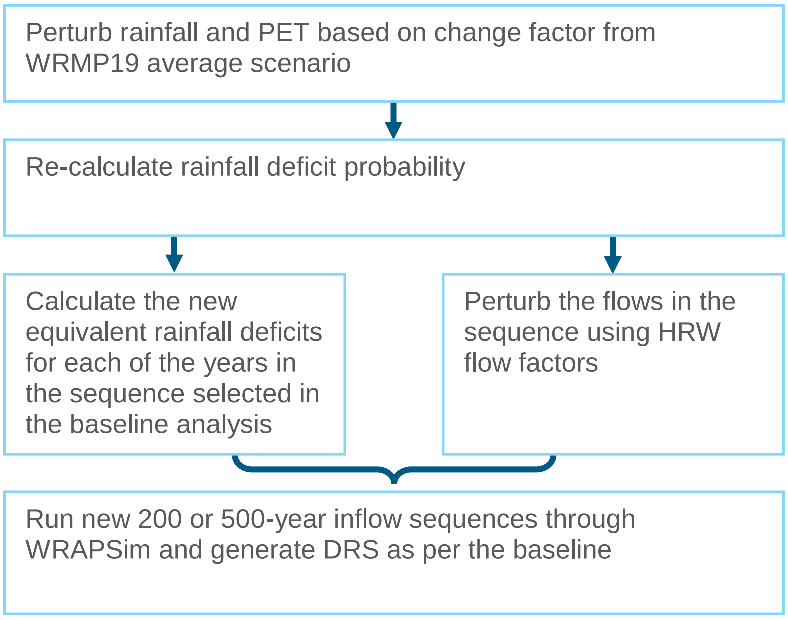


Figure 4-45 - Summary of Climate Change Methodology

Flow factors used from the HR Wallingford report are provided below.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Flow Factor (%)	5.39	8.68	0.42	-2.57	-10.9	-16.07	-9.82	-18.89	-16.96	-10.15	7.97	9.77

4.9.4. Results

Drought Risk Analysis

There are a range of failures in aggregate storage across all durations and month endings in this WRZ. These are more effectively summarised as a DRS and are therefore presented and explained in the following section.

Failures in Llys-Y-Fran and the aggregate storage are well correlated. It is worth noting that the reservoir storage responses tend to support the DRS, in so much as there is relatively little variation in risk across the range of drought durations tested. As an example, simulated storage is shown for Llys-Y-Fran (Model 5N, baseline, droughts ending September) in Figure 4-46 and for aggregated storage in Figure 4-47.

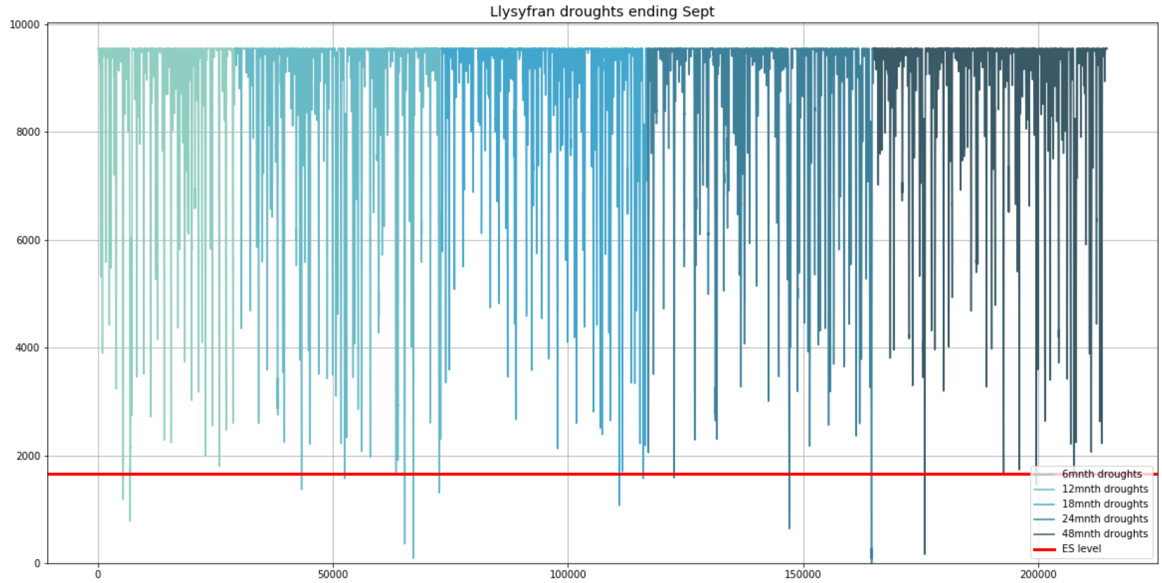


Figure 4-46 - Example of the Drought Library Timeseries for Llys-Y-Fran Reservoir (Model 5N baseline, droughts ending September)

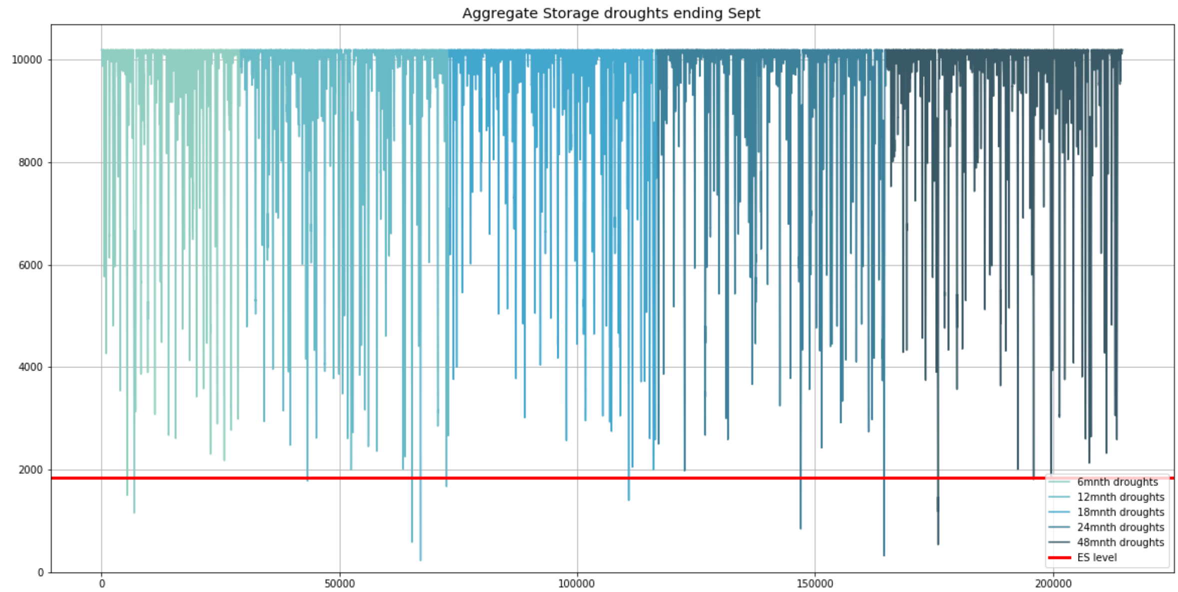


Figure 4-47 - Example of the Drought Library Timeseries for aggregated storage (Model 5N baseline, droughts ending September)

Drought Response Surfaces

As shown in Figure 4-48, under the current system and climate change (5N) model setup the risk of failure is greatest for 12 to 24 month drought events, with non-trivial failures experienced at the 1 in 200 year return period level. The risk is more notable for ‘ending October’, and is more concentrated in the 12 and 24 month durations.

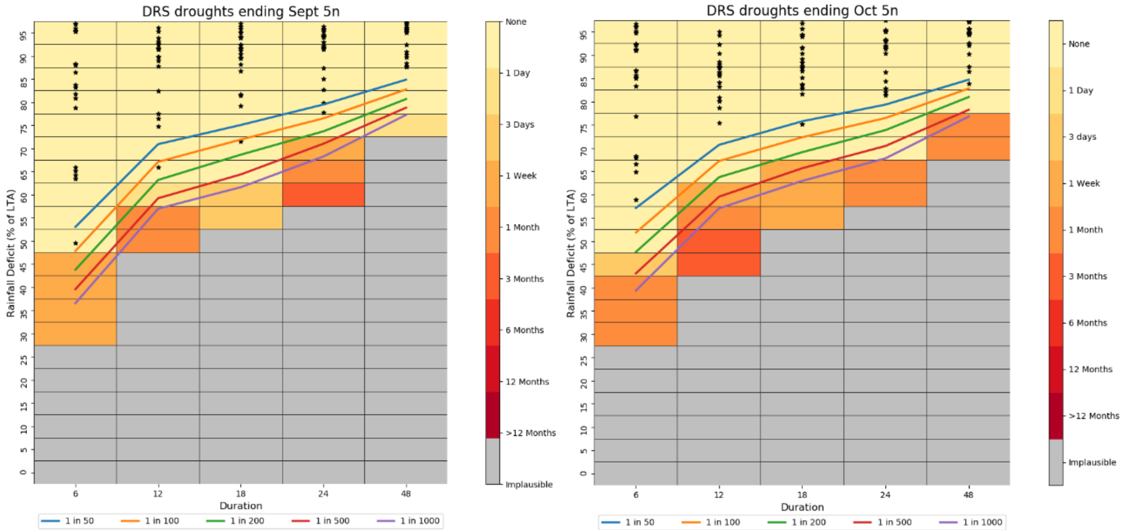


Figure 4-48 - Baseline DRS for Model Setup 5N

As noted previously, the introduction of the flexible pumping arrangements has a very significant effect, so that there were no failures within the testing of the drought library in the baseline scenario.

Under the climate change scenario, risks increase notably under the current system setup (5N), as shown in Figure 4-49 below. Non-trivial failures start to occur within the 1 in 50 events across the shorter duration (6 and 12 month) droughts. The risks start to become worse in the ‘ending September’ scenario, as a result of the increasing intensity of the spring/summer part of the drought. It should be noted that the shape of the DRS does change under the climate change scenarios. This is observed in other WRZs and comes from the fact that the deficits are calculated in proportion to the baseline (1961-1990) climate. Because climate change introduces wetter winters but drier summers, then the 6 and 18 month ending scenarios become notably worse, whereas the 12 and 24 month scenarios actually reduce in range. The effect is much more notable in the 5N model setup than it is the 5M model setup – this is a reflection of the two different climate change scenarios that were used and shows how big the effect of climate change can be on the basic nature of drought across WRZs. Clear failures are seen under the climate change scenario for rainfall deficits with a much lower return period – this is due to the effect of increasing PET, which affects the flow and hence storage risk, but is not obvious in the rainfall deficits.

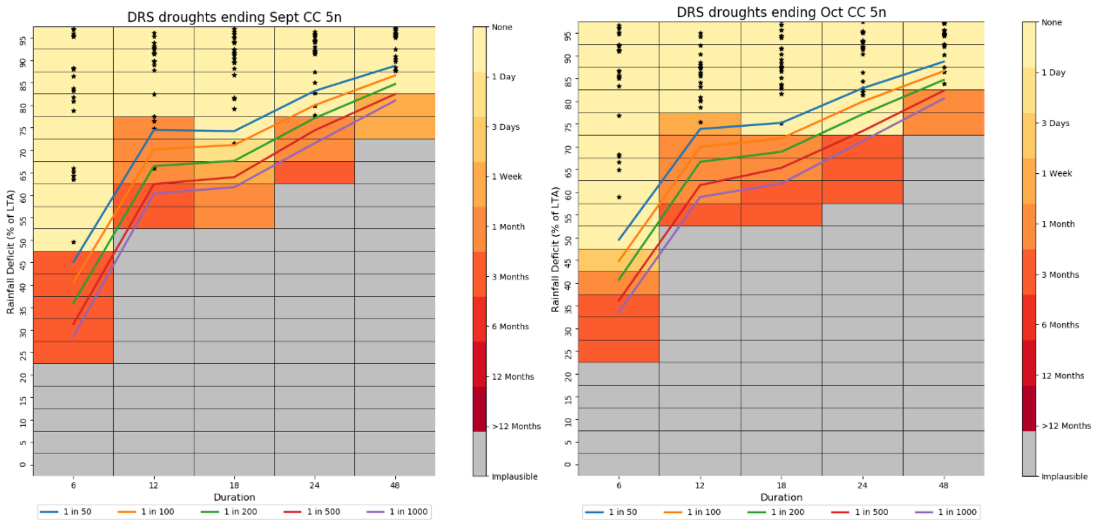


Figure 4-49 - 2030s Climate DRS for Model Setup 5N

Under the 5M model setup failure risks are seen, but these are much less significant and remain at or below the 1 in 200 year event risk.

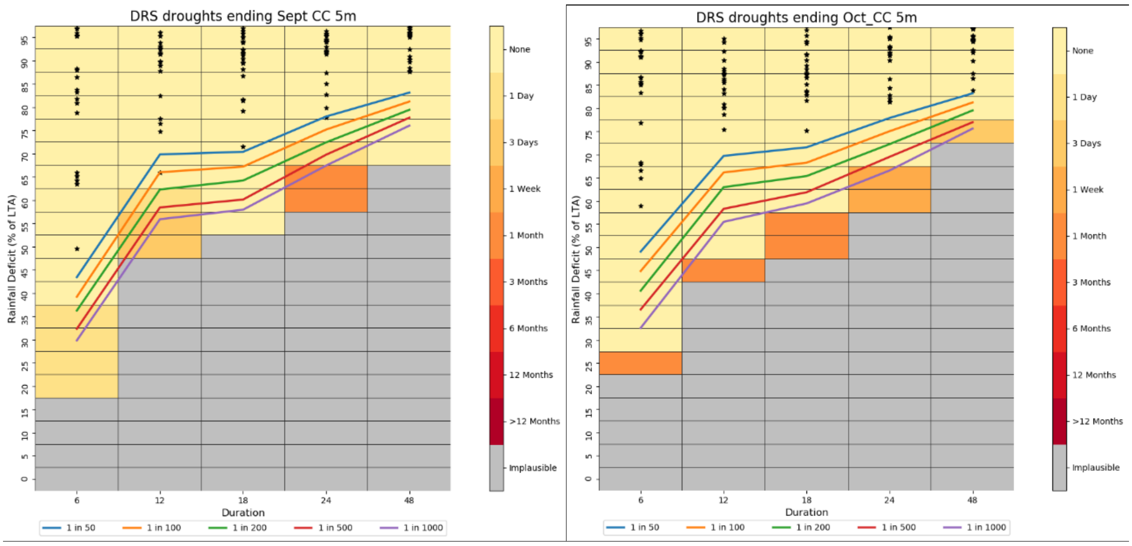


Figure 4-50 - 2030s Climate DRS for Model Setup 5M

4.10. Brecon Portis

As noted in Section 2.2, abstraction at Brecon is only at risk if the Usk reservoir is unable to release to the river during extreme drought events. The outputs of the SEWCUS model (Section 4.12) were therefore analysed to determine this risk.

As shown in Figure 4-51 below, the Usk reservoir could feasibly become empty during extreme droughts. However, this needs to be viewed in the context of the overall SEWCUS WRZ. As shown by the DRS in Figure 4-69, at an aggregate storage level, drought risk in the SEWCUS WRZ is extremely low. There is only one isolated failure in droughts ending in September, and this only occurs once climate change effects are included. This means that in reality, regulation of the River Usk for abstraction in the SEWCUS WRZ would be scaled back slightly to support the relatively small amount of supply required from Usk reservoir for the abstractions at Brecon and the Portis water treatment works. On this basis the WRZ can be considered resilient to plausible droughts and a DRS is not required.

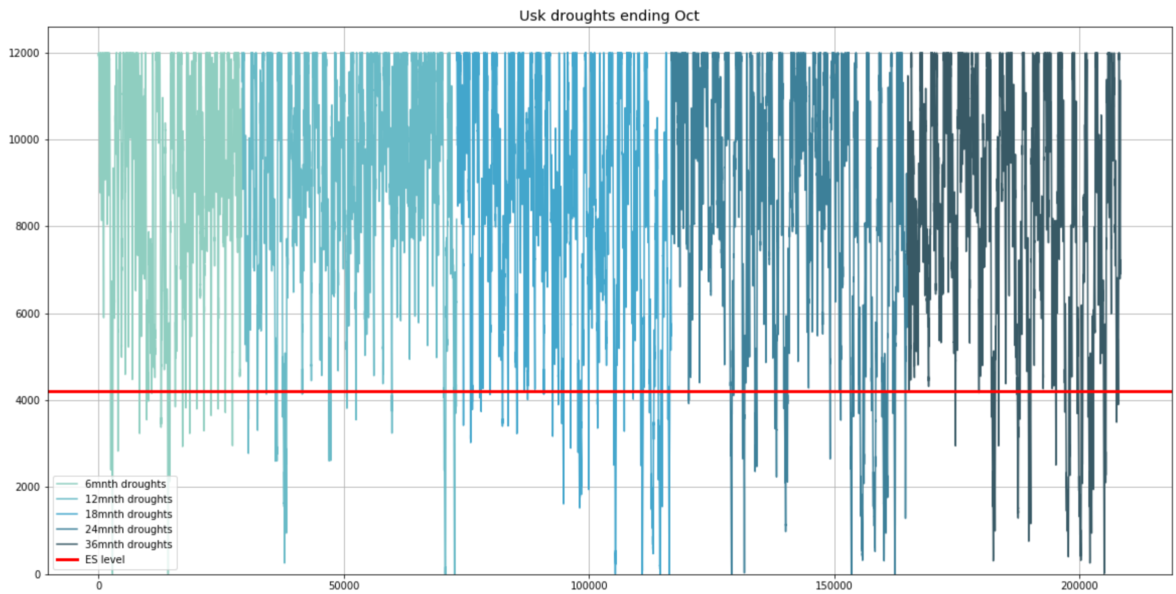


Figure 4-51 – Baseline Usk Storage Plots (droughts ending October)

4.11. Vowchurch

4.11.1. Key Modelling Assumptions

The Vowchurch groundwater abstraction is located close to the River Dore. The aquifer is shallow and consists primarily of alluvial sediments that are hydraulically linked to the river. The sustainability of the groundwater source is therefore dependent on the availability of recharge flow from the nearby river. If the flow in the river falls below the abstraction rate then it is likely that the aquifer will begin to dewater. Currently it is not known what the relationship between this event and drawdown at the groundwater source is, but an analysis of the duration where flows in the river are likely to be below demand (and hence abstraction) is considered to be reasonably indicative of the drought risk faced by the source.

In order to resolve the resilience concerns in the Vowchurch WRZ, DCWW proposes to lay a main to connect it with the Hereford WRZ. As noted in Section 2.2, there is no plausible drought scenario under which flows in the River Wye, the main source of water in the Hereford WRZ, would fall below the abstraction licence limit. Table 4-10 below presents the key assumptions used for the DVF analysis

Table 4-10 - Summary of Key Modelling Assumptions

Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	2.5 Ml/d DYAA	Based on DI, plus Target Headroom, plus outage, process and raw water losses. Demand profile based on WRAPSim.
Durations Analysed	3, 6, 12, 18 months	Small catchment with limited baseflow; analysis is focused on low flow durations
Months Ending Analysed	August, September	Lowest flow periods according to historic data
Failure Criterion	Duration where flows<demand	See above
Climate Change Scenario Used	SEWCUS Set H	Closest climate change modelled catchments. Set H used because it represents lower areas of SEWCUS (more reflective of River Dore orography).

4.11.2. Methodology: Baseline

The methodology used was selected for 3 key reasons:

1. The WRZ is potentially at risk from drought, but there are no hydrological models of the catchment. The method therefore follows the DVF approach 1a full stochastics) but with particular adaptations to account for the issues described below.
2. There is a large amount of uncertainty in the flow record: the gauge that is used in the WRAPSim model is a downstream gauge representing a much larger catchment. The local gauge that has been installed by DCWW has only been operational since 2006 and there are some uncertainties over the accuracy of the data.
3. As it is the duration of the low flow that is important, a method based on monthly flow analysis with a reliable duration assessment was important. Simple re-sampling of the historic record to generate daily flows was not the best approach in this case, as the exact timing of the flow minima in the month was not important (unlike Tywyn Aberdyfi), so a statistically more reliable method of flow percentile analysis could be used.

A summary of the methodology used is provided in Figure 4-52 below.

1. Calculate rainfall deficit/total flow relationships for all scenarios* using the historic record.

2. Generate a stochastic monthly average timeseries for the WRAPSim Dore downstream gauge (10,000 years) using the PARMA functionality within the SAMS modelling package. For each stochastic year, assign a nominal rainfall deficit for each scenario based on the stage 1 analysis.

3. Carry out a comparison of the historic record for the WRAPSim and DCWW local River Dore gauge to generate a monthly based algorithm that converts the WRAPSim equivalent flows into flows local to the groundwater source.

4. For each month, calculate the ratio between the 10th, 25th, 75th and maximum flow percentiles and the monthly average flow based on the historic record. Use this relationship to generate equivalent 10th, 25th, 75th and maximum flows based on the stochastic monthly average record. Calculate the duration of each based on the historic record.

5. For each stochastically generated month, calculate whether the 10th, 25th, mean, 75th or maximum flows fall below demand. Assign that month the relevant number of failure days accordingly. Sum the total number of days failure in each stochastically generated year.

6. Plot the DRS based on the number of days failure and the calculated deficit for each scenario for each stochastically generated year.

**A 'scenario' represents a duration and deficit combination – i.e. one of the cells in the Drought Response Surface*

Figure 4-52 - Summary of Analysis Method

Outputs and comments from Stages 1 to 5 are provided below.

Stage 1: Calculation of Rainfall Deficit/Flow Relationships

The historic record was used to derive a relationship between the monthly flow for the 'month ending scenario' (i.e. August or September) and the antecedent 3, 6, 12 and 18 month rainfall. This relationship was generated according to both the expected value (central model estimate) and the range of uncertainty in that relationship. This was used when rainfall deficits were being assigned to each stochastically generated flow year in Stage 2.

In order to determine the probabilities of the rainfall deficits in each cell of the DRS, extreme value analysis for each duration and month ending was carried out on the historic record (taken from the GEAR data set). Illustrative outputs from that analysis are provided in Figure 4-53 below.

It should be noted that there was a clear change in the distribution at around the P X<x = 0.15 mark (i.e. the lowest 15% of records), particularly for the 'month ending' August scenarios. A 'points over threshold' analysis was therefore used whereby the Weibull distribution was fitted to the lowest 15% of values. This clear change in behaviour between dry and normal/wet conditions is likely to be related to the fact that Vowchurch is in the rain shadow of the Black mountains, so the statistical behaviour during weaker frontal and blocking high pressure periods will be different to the behaviour when there are strong Atlantic rainfall episodes in the data.

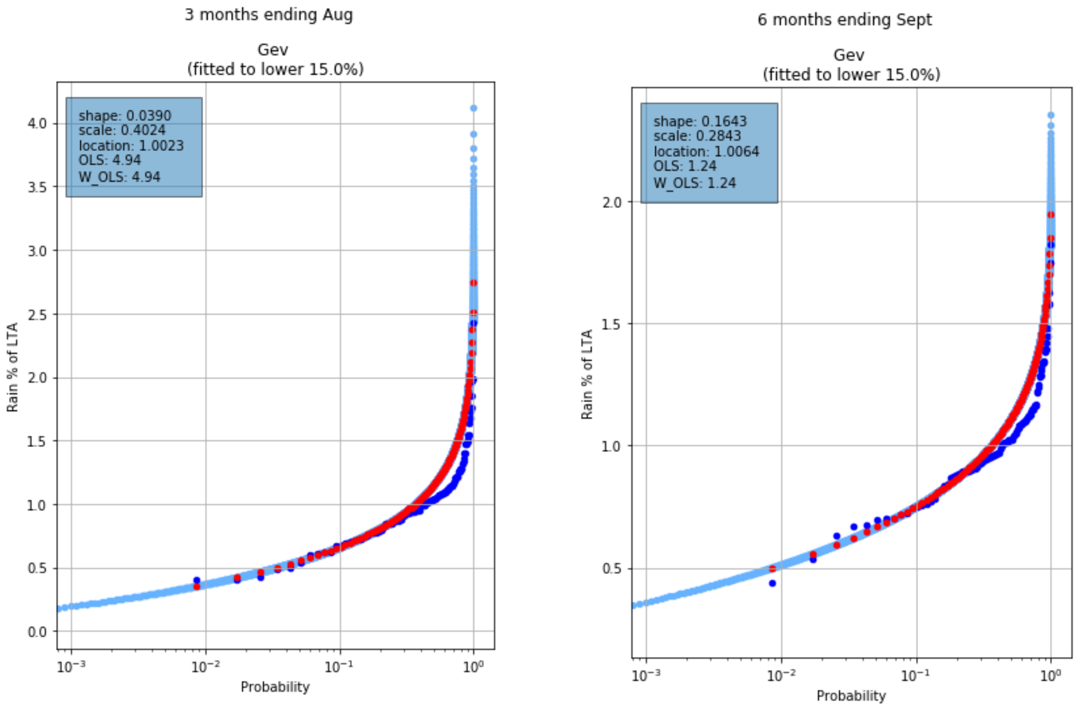


Figure 4-53 - Examples of the Final GEV Plots for Rainfall

Stage 2: Generation of Stochastic Flow Records

The generation of the stochastic flow records was straightforward and produced a reliable fit. Output charts for the summer months are provided in Figure 4-54 below.

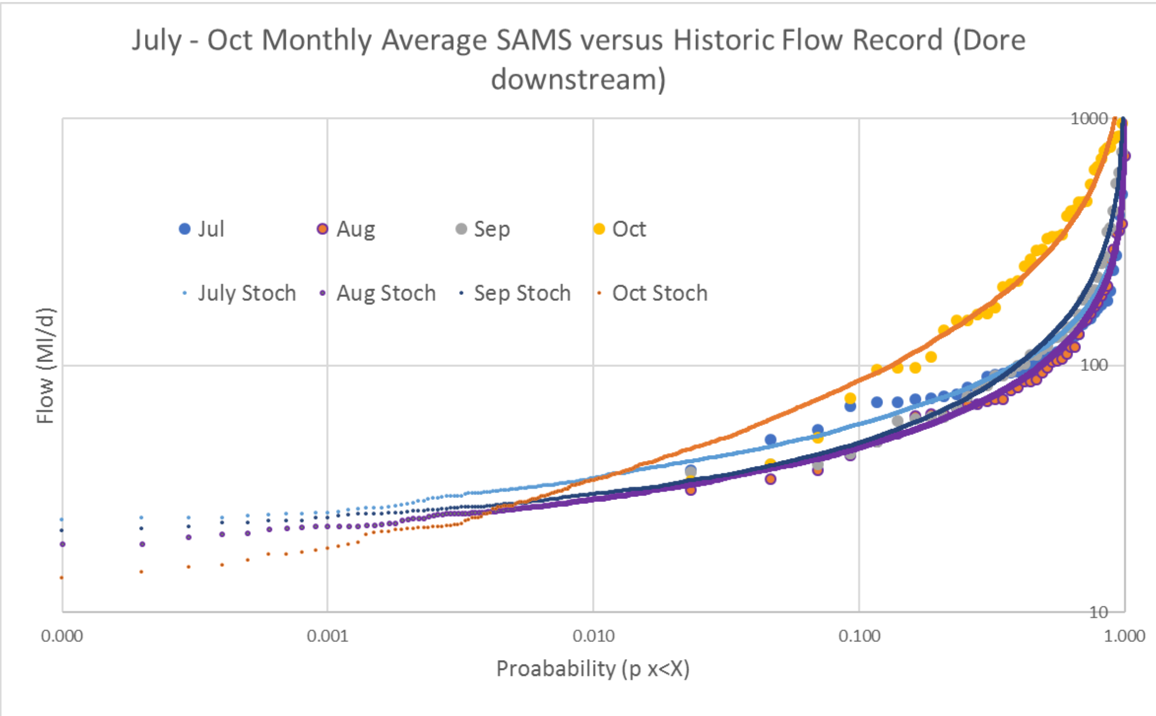


Figure 4-54 - Historic Record versus SAMs Generated Flow (Dore downstream gauge)

Each stochastically generated year was assigned the appropriate rainfall deficit based on the flow versus deficit relationship calculated for the historic record derived during Stage 1. In order to reflect the random variability in the relationship, each flow year was randomly assigned a deficit equal to either the 25th, 50th or 75th percentile of the potential range.

Stage 3: Catchment Size Adjustment

A chart comparing the locally recorded flows (in place since 2006) with the downstream longer-term gauge (River Monnow at Grosmont) used in WRAPSim is provided in Figure 4-55 below. The locally recorded flows have been naturalised by adding back in the estimated abstraction (taken as the Distribution Input from the WRMP). The naturalisation could potentially be improved by using actual abstraction data, however the approach taken here is satisfactory for the purposes of this assessment.

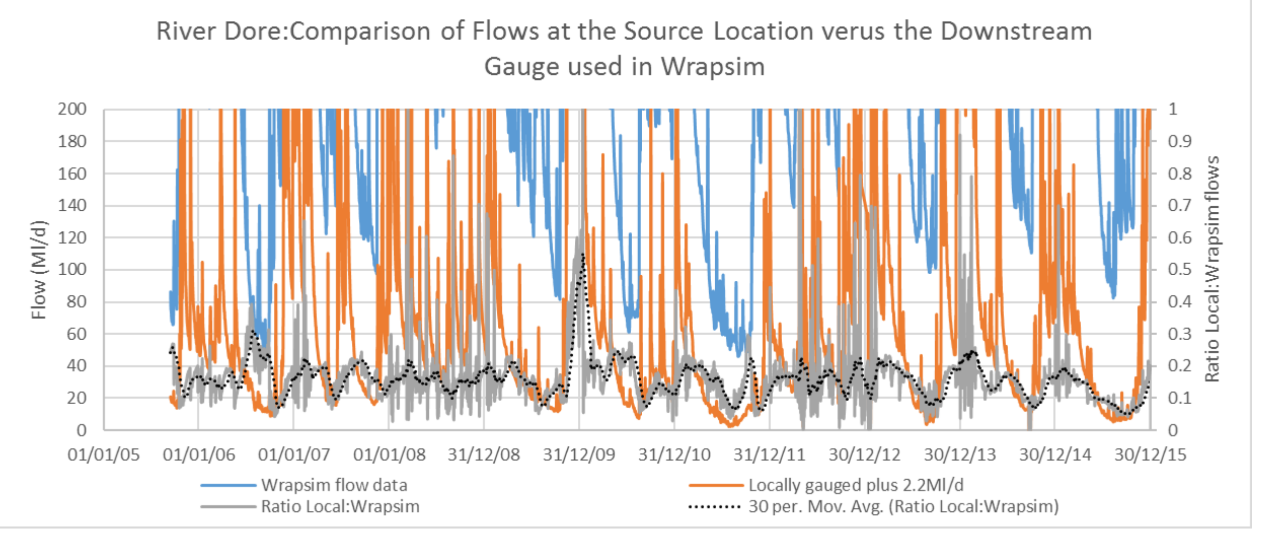


Figure 4-55 - Comparison of Gauging Sites on the River Dore

As shown, the ratio between the two gauges varies randomly on a daily basis as a result of differing speed of response to rainfall, however the monthly average typically varies from around 0.2 under wetter conditions down to just below 0.1 under low flow conditions. A simple algorithm was therefore developed from the recorded data that calculates the ratio between the two sites, based on the flow conditions in the downstream gauge. This algorithm was based on regression of the historic record and took the form:

$$y = 0.0003x + 0.0835$$

where

- y = flow in the local gauge (Ml/d)
- x = flow in the downstream WRAPSim gauge (Ml/d)

Stage 4: Calculation of Monthly Flow Percentiles

The historic flow record was analysed to identify the ratio between monthly average flow and the 10th, 25th, 75th and 100th (maximum) of daily flows for each individual month in June, July, August, September and October. As this relationship tended to change between higher flows and the low flow conditions that were the focus of this analysis, the analysis and generated algorithms were based on low flow months only. An example of the analysis is provided in Figure 4-56 below.

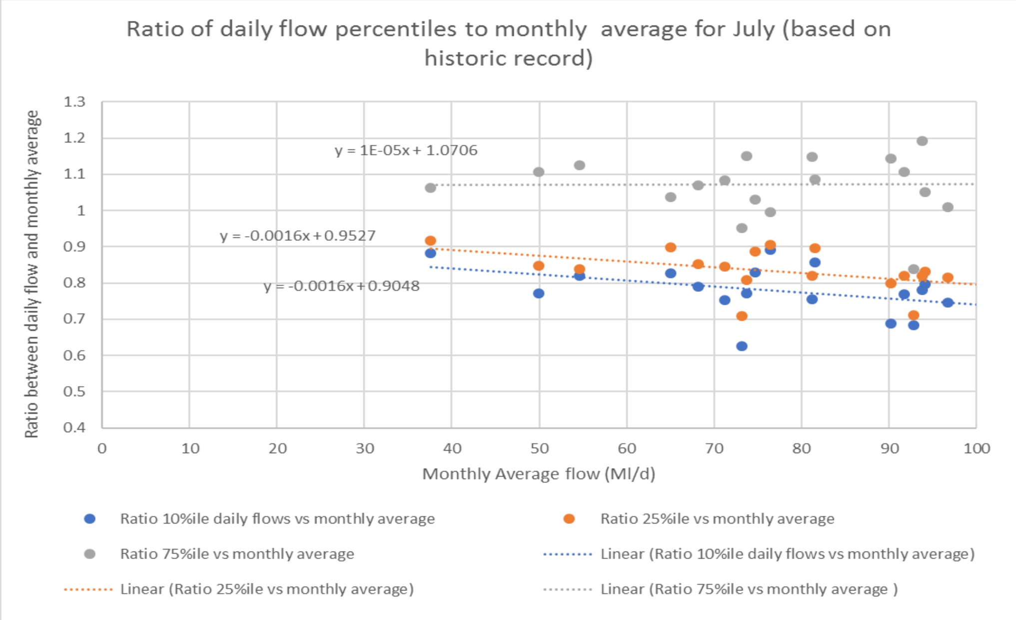


Figure 4-56 - Example Percentile Ratio Output

The average number of days where flows fell below the relevant percentile for each month was also calculated, typically 3 days for the 10th percentile, 8 days for the 25th percentile and 23 days for the 75th percentile. Daily flows fell below the monthly average for around 20 days in each month.

Stage 5: Calculate Failure Durations for Each Stochastically Generated Month

For each of the SAMS downstream River Dore stochastically generated monthly average flows, the equivalent percentiles for the local gauge were calculated using the following formula:

$$PF_i = SAMS_i * loc\ func(SAMS_i) * percfunc(month)$$

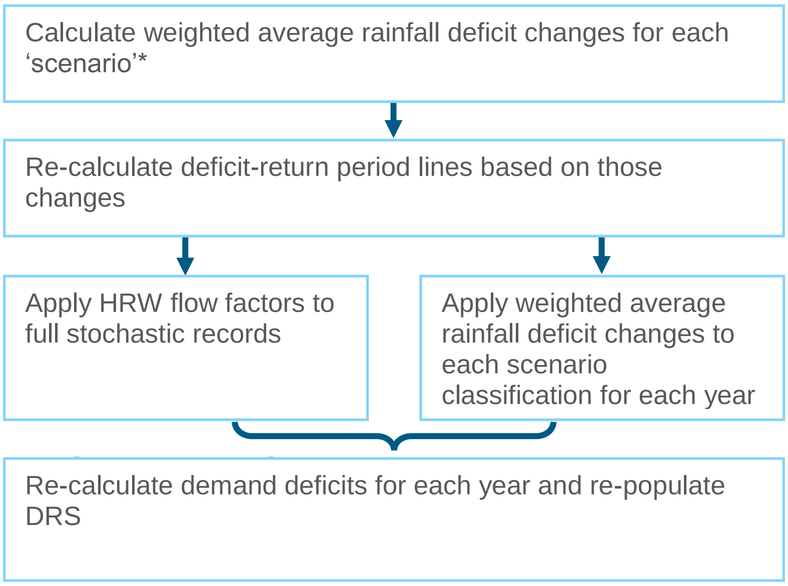
Where:

- PF_i = percentile flow for month i (10th, 25th, 75th and max calculated for month i)
- $SAMS_i$ = SAMS generated flow for month i
- $loc\ func(SAMS_i)$ = location function, calculated based on the SAMS generated flow for month i
- $perc\ func(month)$ = percentile function, calculated according to the calendar month (June, July etc)

The flow for each percentile was then compared against the demand level for that month. The highest percentile where failure occurred then determined the duration of failure for that month (i.e. if flows were only lower than demand for the 10th percentile, then the estimated failure duration was 3 days for that month). The total number of failure days for each stochastically generated year were then added together based on the monthly totals in that year.

4.11.3. Methodology: 2030s Climate

The impact of climate change on rainfall deficits and flows was carried out using the general methodology shown in Figure 4-57.



** the weighted calculation is used to calculate the percentage rainfall change for each duration and month ending scenario, using the HRW rainfall perturbation factors, and the equation:*

$$\%\ change\ in\ rainfall\ for\ scenario\ x = \frac{\sum_{i=1}^{n}(rain * \%change)_{month\ i}}{\sum_{i=1}^{n}(rain)_{month\ i}}$$

Where scenario x = a given combination of duration and month ending (e.g. 6 months ending August)

Figure 4-57 - Climate Change Attribution Method

The WRMP19 climate change analysis did not cover Vowchurch, so factors from the nearest lowland location, SEWCUS set H, were used as a proxy.

The failure probability-duration analysis was re-calculated by applying the following climate change factors to each SAMS stochastically generated monthly average flow (this represents the average expected climate change impact across all flows, as detailed in the HR Wallingford WRMP19 report):

Month	J	F	M	A	M	J	J	A	S	O	N	D
Flow Factor (%)	5.39	8.68	0.42	-2.57	-10.9	-16.07	-9.82	-18.89	-16.96	-10.15	7.97	9.77

4.11.4. Results

Drought Risk Analysis

The absolute system probability-duration failure output for the baseline (no climate change) scenario is shown in Figure 4-58 below. This shows that during a 1 in 50 year event it would be expected that flows would fall below the abstraction rate (at 2.5 Ml/d) for around 20 days in the year. For a 1 in 200 event this increases to around 30 days.

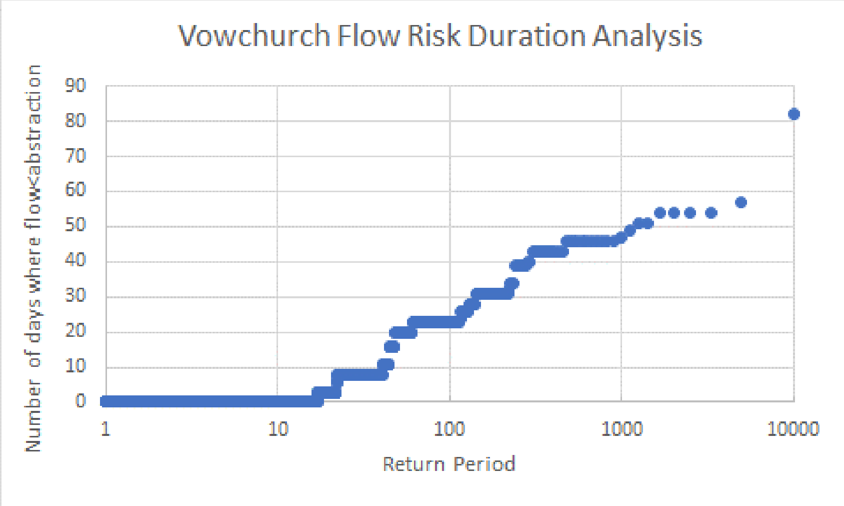


Figure 4-58 - Supply Risk Analysis without Climate Change

The impact from climate change on the probability-duration failure analysis is shown in Figure 4-59 below. This shows that under 2030s climate change, the expected duration where flows would be less than abstraction during a 1 in 50 year event increases to around 30 days. For a 1 in 200 year event the expected duration increases to around 50 days.

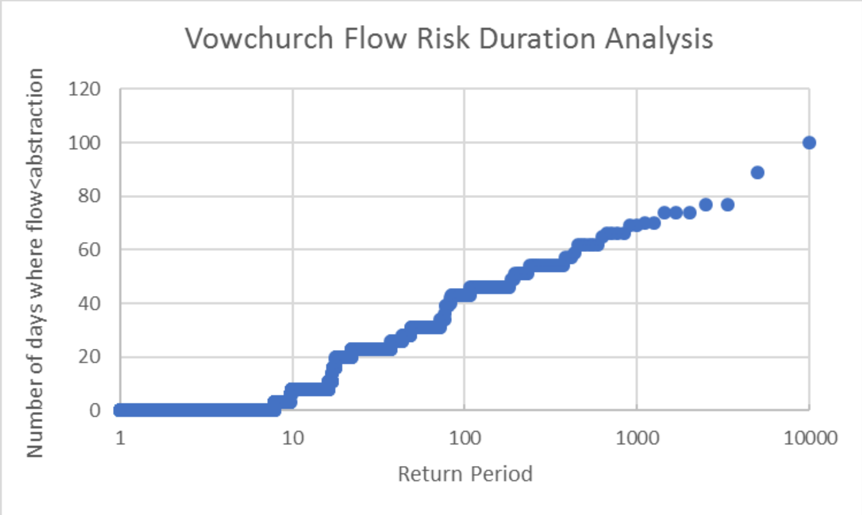


Figure 4-59 - Supply Risk Analysis with 2030s Climate Change

Drought Response Surfaces

The DRS with and without climate change are provided in Figure 4-60 and Figure 4-61 below. It should be noted that in this case 'failure' represents the expected duration where flows in the River Dore at the abstraction site will fall below the 2.5 Ml/d calculated demand level. The impact that this might have on the groundwater source is not known at this stage.

Marginal failures occur at relatively low return periods purely because of the flashy nature of the catchment. For example, even for the 3 month analysis it is entirely possible for a generally dry year to have at or above normal rainfall in June, but still result in flows below the threshold for a few days if July and August are exceptionally dry. It is also likely that the quality of data used affects the marginal failures, as there was a large scatter between flow and rainfall in the historic record (for example, August 1976 showed rainfall of 88mm at the gauge used, even though August 1976 resulted in the lowest monthly flow on record).

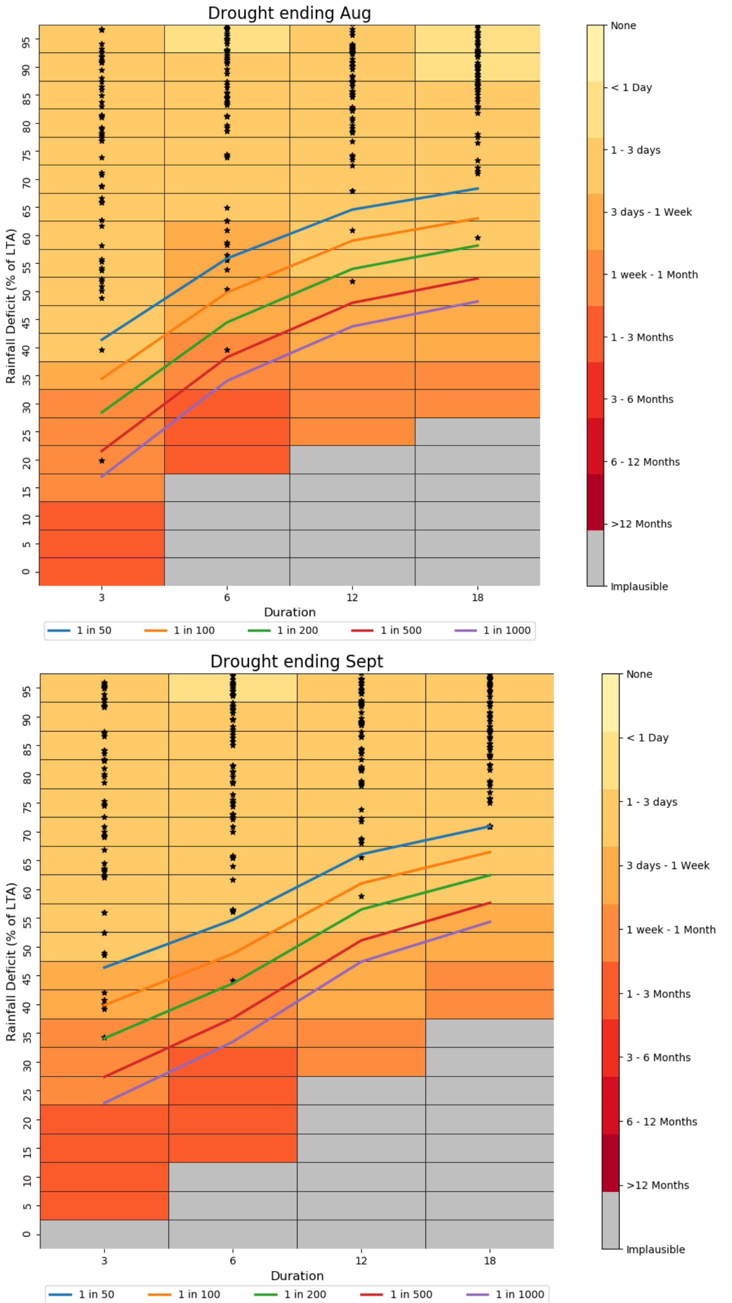


Figure 4-60 - Drought Response Surfaces for Baseline

The key conclusion that can be drawn from the analysis is that significant risks (flow < demand for more than 1 week) will only tend to occur during rainfall deficit events of 1 in 100 or more, but these can develop quickly, for durations of 6 months or less. The risk is similar for the period ending August and September – i.e. such events will tend to happen during dry periods that extend into the late summer.

The DRS outputs with 2030 climate change factors applied are shown in Figure 4-61. These show that the risk from summer droughts increases significantly, with 1 in 50 events generating potential low flow periods of more than a week, and events lasting more than a month occurring at the 1 in 200 year frequency.

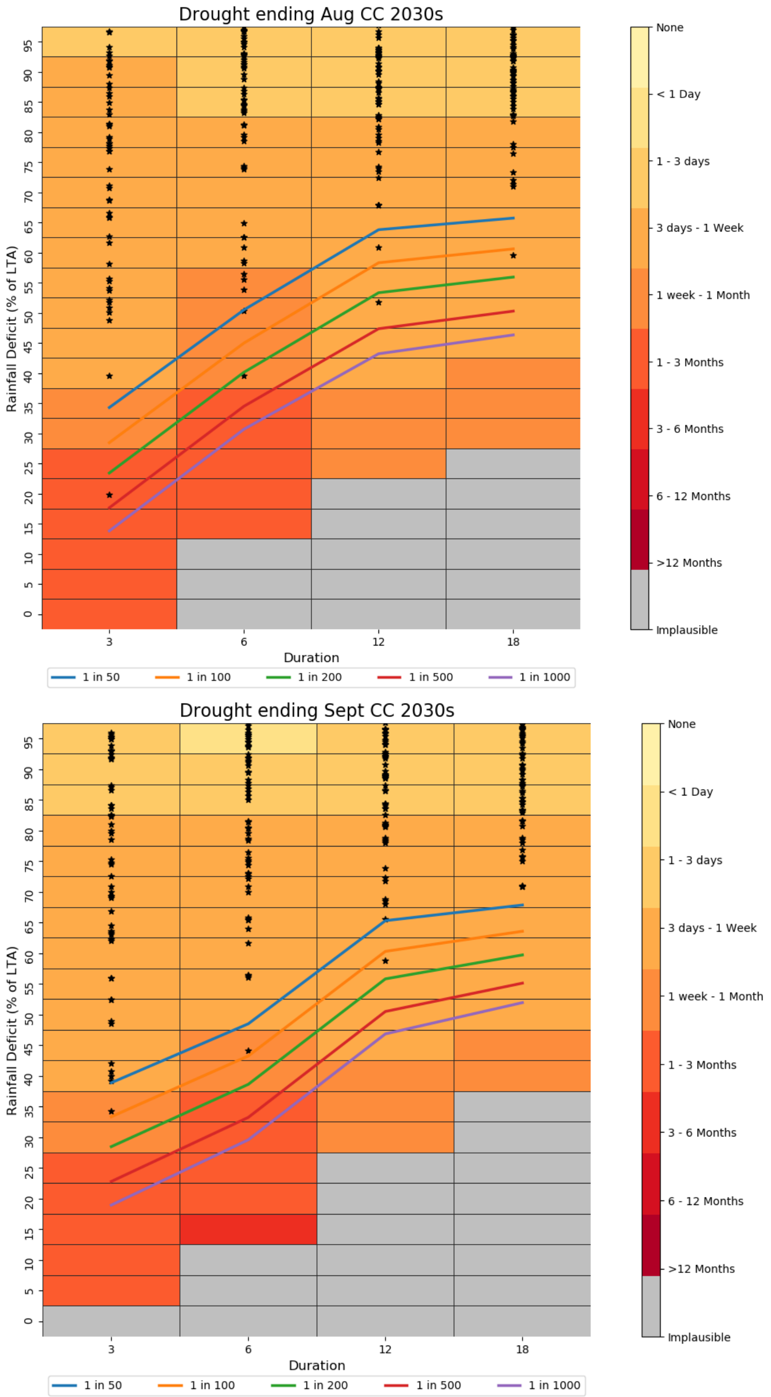


Figure 4-61 - Drought Response Surfaces for 2030s climate

4.12. SEWCUS

4.12.1. Key Modelling Assumptions

SEWCUS is a large conjunctive-use water resource zone (WRZ) with a range of surface water sources including the “Big 5” reservoir group and abstractions from the Rivers Wye and Usk. This WRZ has been assessed as higher risk due to its size and complexity and a relatively small supply demand surplus. Table 4-11 below presents the key assumptions used for the DVF analysis

Table 4-11 - Summary of Key Modelling Assumptions

Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	411.12 Ml/d DYAA	Based on DI, plus Target Headroom, plus outage and process losses. Demand profile based on WRAPSim.
Durations Analysed	6, 12, 18, 24 and 36 months	Storage relies on high rainfall in the mountains, so can be vulnerable to quite short duration, but very high intensity, drought events
Months Ending Analysed	September, October, [November]	Lowest flow periods according to historic data – some uncertainty over individual reservoir responses so three months ending tested in this case
Failure Criterion	Duration where flows<emergency storage	Failure of emergency storage across the ‘Big’ 5 reservoir group (emergency storage = 30 days demand)
Climate Change Scenario Used	UKCP09 1006	This represents the 50th percentile scenario (central estimate) of the 20 UKCP09 scenarios used to determine deployable output impact in WRMP19.

4.12.2. Methodology: Baseline

Due to the perceived level of drought risk in the WRZ, it was analysed using DVF method 1b (direct stochastic generation of flows). The exact methodology that was used was selected for 2 key reasons:

1. The WRZ is potentially at risk from drought, but there are no rainfall-runoff models, so multi-site direct flow generation using SAMS was required.
2. The impacts on yield and system failure need to be run through WRAPSim, so a ‘drought library’ approach was needed to sample representative droughts from the full SAMS data set.

A summary of the methodology that was adopted for SEWCUS is provided in Figure 4-62 below.

1. Calculate rainfall deficit/total flow relationships for all scenarios using the historic record.

2. Generate a stochastic monthly average timeseries across all of the WRAPSim input catchments. For each stochastic year, assign a nominal rainfall deficit for each scenario based on the historical relationship.

3. Use the lookup matrix to select an appropriate number of drought events in each rainfall deficit/duration for testing in WRAPSim

4. Generate a drought library timeseries input, based on the selected drought events and the lookup table of warm up and cool down requirements for the different drought durations.

5. Run the 500 year drought library through WRAPSim. Review results and examine both aggregate 'Big 5' failures against emergency storage and individual reservoir responses.

6. Plot the DRS based on the number of days failure and the calculated rainfall deficit for each scenario for each stochastically generated year.

Figure 4-62 - Summary of Analysis Method

Outputs and comments from Stages 1 to 6 are provided below.

Stage 1: Calculation of Rainfall Deficit/Flow Relationships

A relationship between rainfall and flow was calculated from the historic record based on total Senni flow (the main source of inflow data for the WRAPSim model) and rainfall deficits across 6, 12, 18 and 36 months for each of the 'month ending' scenarios (i.e. September, October and November).

For the October and November 'month ending' scenarios the relationship was generated according to both the expected value (central mode estimate) and the range of uncertainty in that relationship. This was used to assign rainfall deficits to each stochastically generated flow year as outlined in method 2 of Stage 2 below.

A weighted extreme value approach was used to determine the probabilities of the rainfall deficits in each cell of the DRS and for each duration and month ending. Under this approach a Weibull distribution was fitted to the historical rainfall deficits but with a higher weighting applied to the bottom 10% of data. Illustrative outputs from this analysis are provided in Figure 4-63 below.

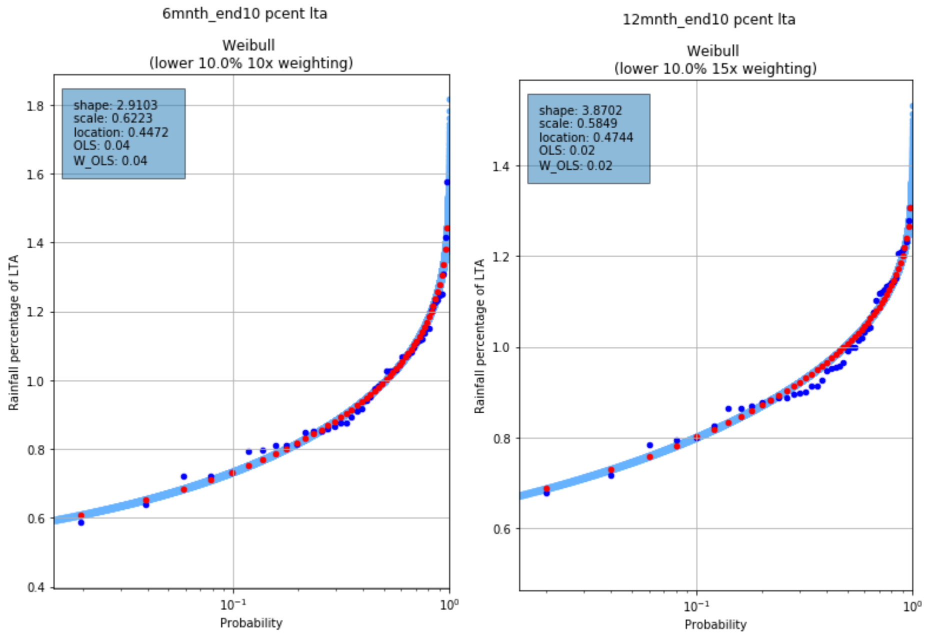


Figure 4-63 - Examples of the Final EVA Plots for Rainfall

Stage 2: Generation of Stochastic Flow and Assignment of Rainfall Deficit

The stochastic generation of flows had already been carried out for SEWCUS as part of the WRMP19 resilience testing. The process and calibration is therefore fully described in the WRMP19 technical appendix.

In order to fully test the relationship between flow and rainfall deficit, two methods were applied here:

1. A simpler approach, whereby the deficit was calculated simply based on the expected relationship as defined in Stage 1.
2. A percentile led approach, whereby the uncertainty in the historic relationship was quantified, and all stochastically generated years were assigned deficits based on the 25th, mean and 75th percentile of that uncertainty range. In effect this resulted in 30,000 years' worth of generated events.

Stages 3 and 4: Generation of the Drought Library

Because SEWCUS was assessed as a higher risk WRZ, each drought library that was run through SEWCUS consisted of approximately 500 years' worth of generated data. This drought library was sampled from the full stochastic data set based on the matrix shown in Table 3-2.

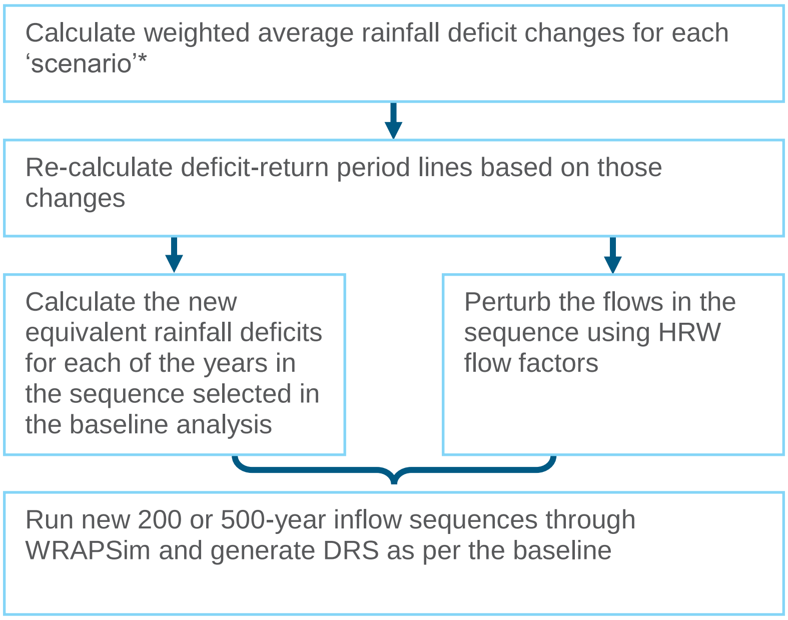
The number of droughts involved was purely a pragmatic decision that balanced the need to fully explore the drought risk in each cell against the run times involved in WRAPSim. As shown, all events up to 1 in 1000 years had at least 4 droughts explored for each combination of rainfall severity and duration, which should be sufficient to identify if there is a significant risk for that type of drought.

Stages 5 and 6: Generation of Failure Data and the Final DRS

These steps were conceptually straightforward. The drought libraries were run through WRAPSim and the volumetric responses in each reservoir at the selected level of demand was recorded. These responses were then examined in a post processing stage to see how long emergency storage values were breached for each drought event.

4.12.3. Methodology: 2030s Climate

The impact of climate change on rainfall deficits and flows was carried out using the general methodology shown in Figure 4-64.



** the weighted calculation is used to calculate the percentage rainfall change for each duration and month ending scenario, using the HRW rainfall perturbation factors, and the equation:*

$$\%\,change\ in\ rainfall\ for\ scenario\ x = \frac{\sum_{i=1}^{n}(rain * \%change)_{month\ i}}{\sum_{i=1}^{n}(rain)_{month\ i}}$$

Where scenario x = a given combination of duration and month ending (e.g. 6 months ending August)

Figure 4-64 - Climate Change Attribution Method

4.12.4. Results

Drought Risk Analysis

The Drought Library events without climate change did not cause any aggregate storage failures, although some did come close (see Figure 4-66). This is due to the forecast 20Ml/d supply demand balance surplus and the conjunctive use flexibility of the WRZ. As a 'sense check' this was compared against the results of the WRMP19 resilience testing, which are replicated in Figure 4-66 below.

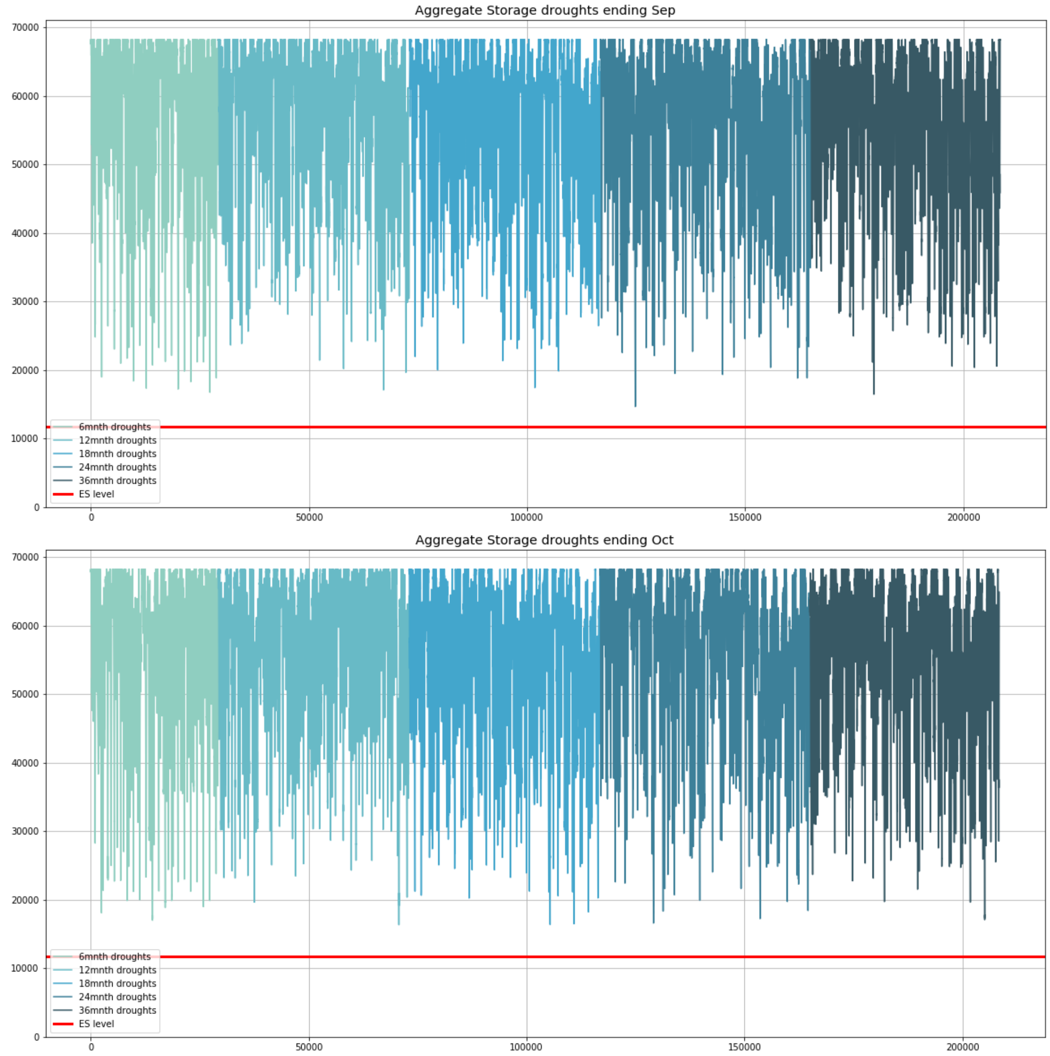


Figure 4-65 - Aggregate Drought Library Results for periods ending September and October

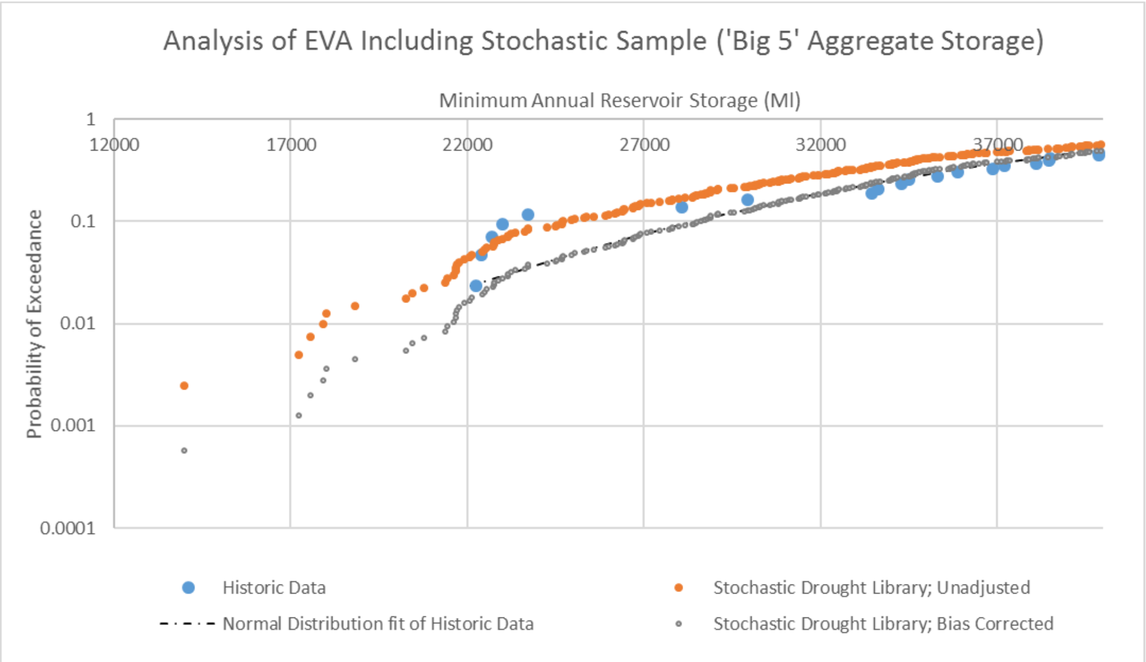


Figure 4-66 - Replication of the Resilience Testing Results from WRMP19

This demonstrates that, in terms of remaining storage, the difference between a worst historic event and an extreme drought event is only in the order of 5,000Ml. Reservoir recession periods are very variable during severe drought events, from as little as 8 months through to 2 or 3 years. This demonstrates that the level of resilience exhibited in the DVF results is expected since, considering the shortest recession period (8 months) against a 5,000 Ml reduction in storage, this implies a yield difference of just over 20 Ml/d (5,000 Ml storage divided by a 240 day recession). Longer and multi-year recession events will have smaller yield reductions, therefore, having 20Ml/d surplus in the supply/demand balance is an adequate buffer against extreme drought events.

Whilst the results without climate change did not lead to emergency storage failures at an aggregate level there were failures in the some of the individual reservoirs, indicating possible localised resilience issues. Statistics from the WRAPSim runs are shown below in Table 4-12 to Table 4-14 (drought libraries with events ending in September, October and November respectively). Each 571-year drought library contains events with a severity of 1 in 50 years or above in terms of rainfall deficit.

Failures occurred in at least one event and drought library in all the Big 5 reservoirs except Llandegfedd, although the scale of failures varied significantly between reservoirs. The reservoir with the largest extent of failures for the periods ending September and October was Usk. In the drought library with events ending in September it had periods of failure exceeding a year in length and occurring in almost 70 of the 571 years. In rainfall terms, the least severe of the events which caused a failure has a return period of 1 in 84 years. For Llwynon there were less extensive failures in events ending September and October but had failures exceeding a year in length in the period ending November. Ponsticill also had larger failures in the period ending November although to a smaller extent with the maximum duration being 57 days with the least severe of these at a 1 in 60 return period. Cantref had just one failure event in the 'ending November' drought library.

Table 4-12 - SEWCUS individual reservoir results – library with droughts ending in September

Reservoir	Cantref	Llwynon	Llandegfedd	Usk	Ponsticill	Talybont
Emergency storage (Ml)	73.3	876	2733.2	4216	2513.3	1277.1
Number of failure days	0	132	0	12671	10	0
Average duration (d)	0	9	0	104	10	0
Maximum duration (d)	0	44	0	594	10	0
Number of droughts with failure (/571)	0	12	0	111	1	0
Highest (most frequent) return period with failure	No failures	1 in 75 years	No failures	1 in 83 years	1 in 84 years	No failures

Table 4-13 - SEWCUS individual reservoir results – library with droughts ending in October

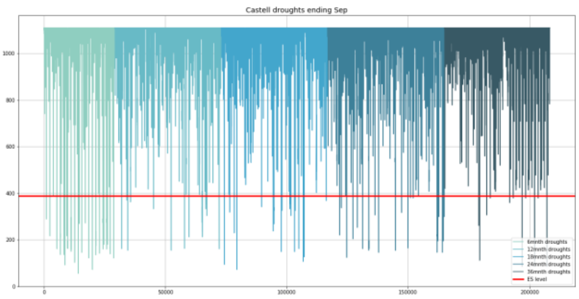
Reservoir	Cantref	Llwynon	Llandegfed	Usk	Ponsticill	Talybont
Emergency storage (Ml)	73.3	876	2733.2	4216	2513.3	1277.1
Number of failure days	0	475	0	2508	0	3240
Average duration (d)	0	23	0	29	0	64
Maximum duration (d)	0	51	0	91	0	208
Number of droughts with failure (/571)	0	24	0	102	0	51
Highest (most frequent) return period with failure	No failures	1 in 89 years	No failures	1 in 83 years	No failures	1 in 10two years

Table 4-14 - SEWCUS individual reservoir results – library with droughts ending in November

Reservoir	Cantref	Llwynon	Llandegfed	Usk	Ponsticill	Talybont
Emergency storage (Ml)	73.3	876	2733.2	4216	2513.3	1277.1
Number of failure days	11	2904	0	0	523	0
Average duration (d)	11	63	0	0	24	0
Maximum duration (d)	11	392	0	0	57	0
Number of droughts with failure (/571)	1	25	0	0	13	0
Highest (most frequent) return period with failure	1 in 110 years	1 in 87 years	No failures	No failures	1 in 60 years	No failures

This indicates that in general the 'ending September' risk tends to be higher than the later ending drought risk. That is not particularly surprising because of the relatively high rainfall associated with the mountainous nature of the reservoir catchments. These factors mean that the resource position in October will, probabilistically, tend to be better than at the end of September due to the relatively good chance that rainfall in October will be high enough to start filling the reservoirs. However, there is clearly some variability in vulnerability to failure events between the reservoirs with Llwynon and Ponsticill both exhibiting more extreme failure events in the 'ending November' library.

Of the non-Big 5 reservoirs three exhibited failures in both the droughts ending September and ending October periods. These were at Castell Nos, Elan and Llyn Fawr. These are shown for the ending September library in Figure 4-67 below.



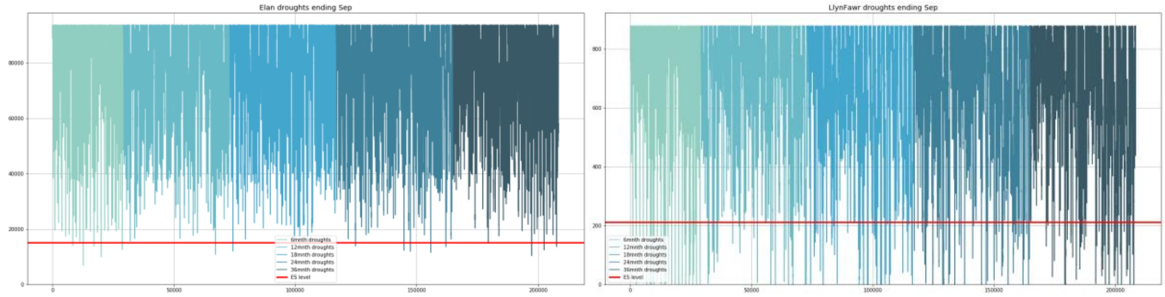


Figure 4-67 - Drought Library Results for period ending September for Castell Nos, (top left), Elan (bottom left) and Llyn Fawr (bottom right)

With the inclusion of climate change there are a handful of failures against aggregate emergency storage for the most severe events (see Figure 4-68). The resulting DRS is shown in Section 4.12.4.1 below. In terms of individual reservoirs, the number of droughts with failure increases fairly significantly to 38 for Llwynon and 97 for Usk reservoir. The exact return periods for the events have not been calculated. Because of the way that the analysis was carried out the selected droughts should remain at about the same level of severity, so the highest return period of failure is always 1 in 50 or more. However, that does not mean that failures would not occur under more frequent events – it is just that these were not tested as part of the analysis.

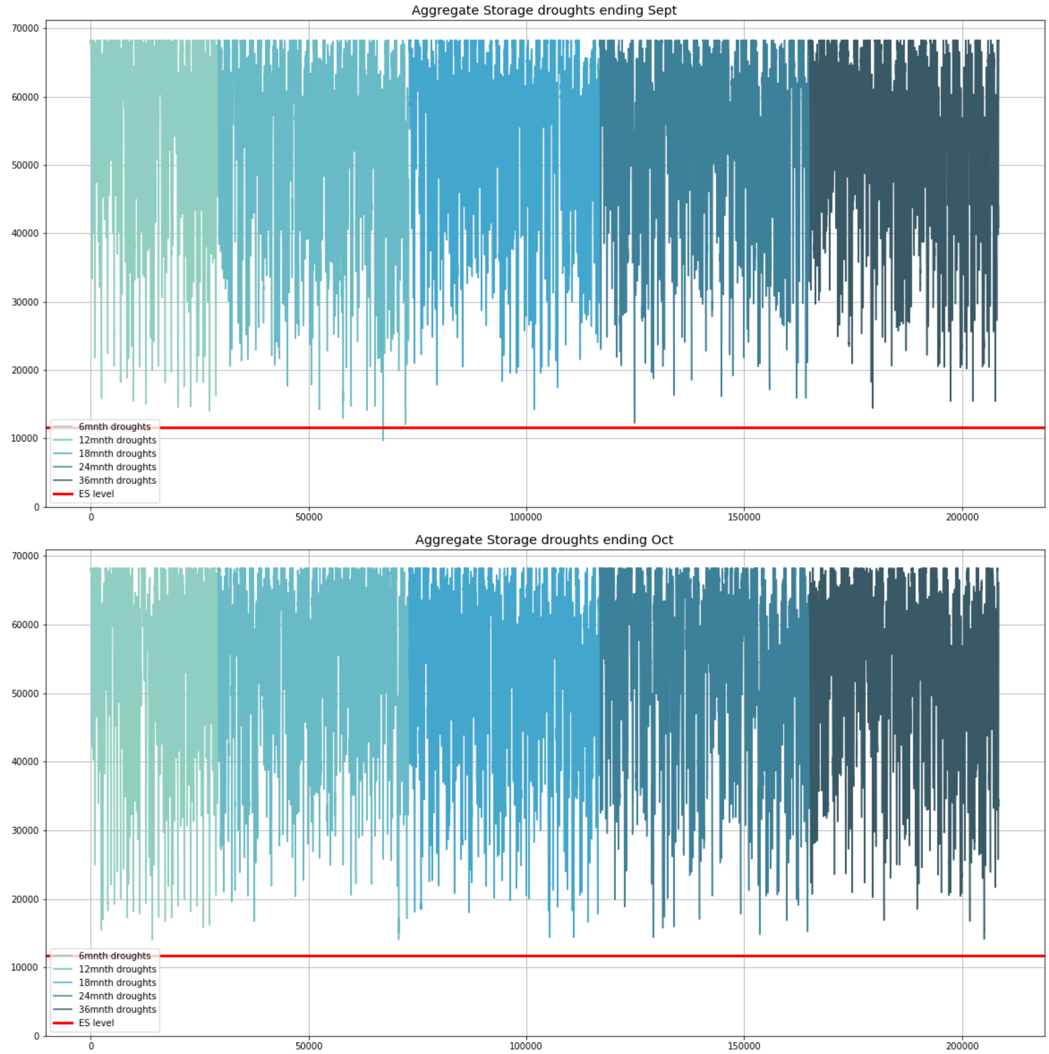


Figure 4-68 - Aggregate Drought Library Results for periods ending September and October with Climate Change

4.12.4.1. Drought Response Surfaces

The results without climate change did not include any aggregate failures of the 'Big 5' emergency storage for any of the month ending libraries, so no DRS was required.

Under climate change some aggregate failures do occur for events ending in September, as shown in Figure 4-69 below, but these are confined to higher return periods and tend to occur during shorter duration events (which are the events most exacerbated by climate change impacts).

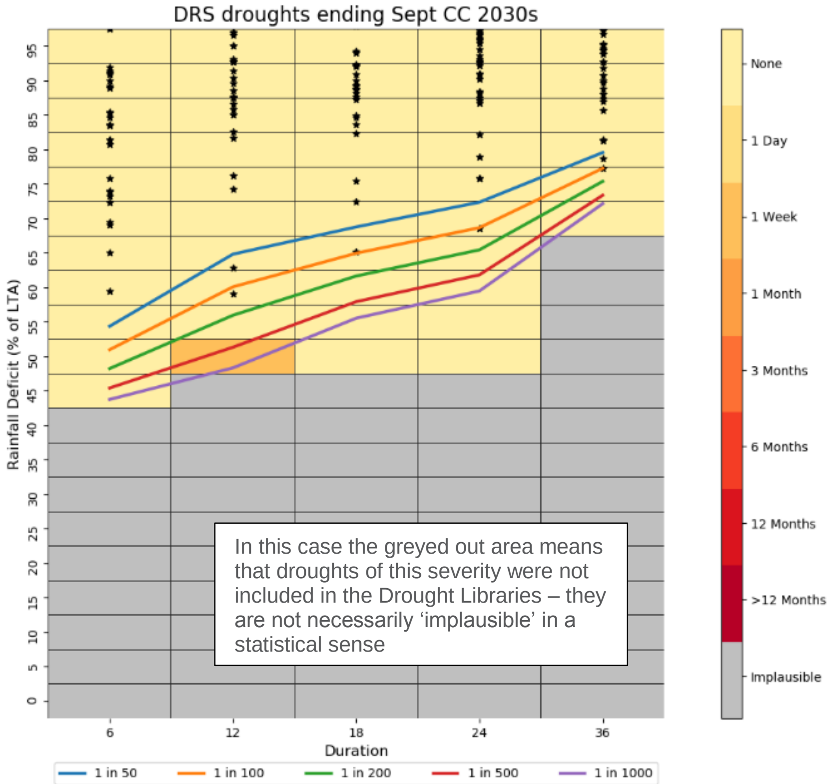


Figure 4-69 - Drought Response Surface for ending September droughts with climate change

5. Conclusion

The DVF has been considered across all of DCWW's WRZs. The process started with a robust and effective screening process, leaving a smaller number of WRZs for further assessment.

Of these, a total of six WRZs required DRS due to failures occurring within the simulation of the stochastic drought libraries, which contain a wide range of different severity events. In many cases the failures occurred only for a very short period of time or at high return periods such as 1 in 500 or 1 in 1000 years. However, the failures were longer and more frequent for Tywyn Aberdyfi, Pembrokeshire and Vowchurch.

In the case of Tywyn Aberdyfi drought resilience risks will be comprehensively mitigated by the planned Afon Dysynni scheme. In Pembrokeshire this assessment showed that the drought risk was significantly reduced by the scheme to improve the flexibility of pumping at Canaston. In the Vowchurch WRZ, DCWW has proposed a supply link from the Hereford WRZ where abstraction from the main source, the River Wye, is not at risk from plausible droughts.

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Appendix 2 WRMP Research, Final Report, December 2017

Dŵr Cymru Welsh Water
WMRP Research

Final Report
~~October~~ December 2017

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CONTENTS

List of Tables

List of Figures

ABBREVIATIONS

CATI	Computer aided telephone interviews
CBA	Cost benefit analysis
DCE	Discrete choice experiment
SP1	Stated Preference Exercise 1
SP2	Stated Preference Exercise 2
SP3	Stated Preference Exercise 3
SP4	Stated Preference Exercise 4
DCWW	Dŵr Cymru Welsh Water
F2F	Face-to-face
PpP	Phone-post/email-phone
PR14	2014 price review
PR19	2019 price review
SEG	Socio-economic grade
SP	Stated preference
UKWIR	UK Water Industry Research
WTA	Willingness to accept
WTP	Willingness to pay
HH	Household(s)
NHH	Non-household(s)

EXECUTIVE SUMMARY

Introduction

Dwr Cymru Welsh Water (DCWW) commissioned Accent and PJM to design and implement a quantitative willingness to pay (WTP) survey. The main aim of this study has been to provide an understanding customers' preferences in relation to the various ways of maintaining or improving the water supply-demand balance as well as with reference to the types of restrictions that might be imposed in a drought situation. Secondary tasks were to explore customers' preferences with respect to improved resilience to the chance of emergency drought restrictions (e.g. rota cuts to supply) and in relation to alternative metering policies. The results provide insights to customers priorities and are thus to be used to both challenge and influence DCWW's water resource management plan and drought plan.

Survey Design and Development

A stated preference (SP) survey was aimed to address the objectives, consisting of four SP exercises:

- SP1 – water resources management
- SP2 – water use restrictions
- SP3 – resilience valuation
- SP4 – metering options.

Prior to the development of the stated preference materials a qualitative phase of work was undertaken to assess customers' initial preference for different demand/ supply initiatives. The qualitative work was also used to help develop the quantitative materials to ensure language used was understandable to customers and the most appropriate supporting graphics/tables were implemented.

SP1 – Water Resources Management

A first discrete choice experiment (DCE) was designed to focus on water resources management options. The options were characterised in this exercise by the combination of supply-demand measures included, the level of service – measured as the frequency of temporary use bans (TUB) for households and the frequency of non-essential use bans (NEUB) for non-households – and the impact on the customers' bill.

The intention in designing the choice exercise in this way was that it would enable WTP estimates to be obtained for the 'external' costs/benefits of each of the included measures, net of their contribution to the water supply-demand balance. By assumption, external effects include all environmental impacts, local disruption effects and any other aspects of the measures that customers approve of or dislike.

These could be obtained, collectively, for each measure by virtue of the fact that the exercise included the frequency of TUBs/NEUBs, so this frequency could be held fixed in the analysis to isolate the external values.

The list of measures was developed in consultation with DCWW to be consistent with the range of measures being evaluated for its water resources management plan.

Respondents were asked to make eight choices in this exercise, where this number was chosen as a reasonable number to balance survey length and complexity against the statistical advantages of greater numbers of observations.

SP2 – Water Use Restrictions

A second DCE was designed to follow the first, within the same survey, to measure customers' views on the types of water uses that should be allowed and prohibited if a TUB, for households, or an NEUB, for non-households, was put in place. In this exercise, the options that were shown were combinations of water use restrictions that would be put in place during a TUB/NEUB, coupled with the expected duration of the ban that would result.

The intention in designing the exercise in this way was that it would enable us to obtain estimates of customers' 'willingness to pay' for alternative water uses during a TUB/NEUB, in terms of the additional duration of the TUB/NEUB that would be acceptable to customers if a certain water use were allowed than if it were prohibited during the ban. The more that customers valued a particular water use, the more extra time they would be expected to be 'willing to pay' to see that water use allowed rather than prohibited.

The potential water use restrictions tested were directly based on those listed in the Flood and Water Management Act (2010) in the case of TUBs, and on those in the Drought Direction (2011) in the case of NEUBs. These water uses also correspond to those listed in DCWW's drought plan. The TUB/NEUB duration attributes took the values 5, 6, 7 or 8 months.

Respondents were again asked to make eight choices in this exercise, where this number was chosen as a reasonable number to balance survey length and complexity against the statistical advantages of greater numbers of observations.

SP3 – Resilience Valuation

The focus of the SP3 exercise was on customers' willingness to pay for an improvement in drought resilience, as measured by the expected frequency of rota cuts to supply. Specifically, respondents were asked about their willingness to pay for an improvement in the risk of rota cuts from 1 in 100 to 1 in 200.

Analysis of these questions allows us to obtain an estimate of mean WTP for the improved level of service and, in addition, an estimate of the proportion of customers that would be willing to pay given levels of bill increases.

SP4 – Metering Options

The final SP exercise in the survey related to customers' preferred choice of metering policy. Customers were given three options and asked which they would most like to see, and which they would least like to see. The options shown were the following:

Table 1: Metering options

1	A compulsory metering policy, where all customers are billed by a meter without choice. Under this scenario customers would receive information on their water use delivered via a mobile phone app, or an online account. Customers would also receive a water efficiency audit to resolve any leaks, and to install water efficiency products to help manage their water use.
2	A progressive metering policy where all customers are metered, but have a 2 year adaption period to a measured basis (unless they prefer to swap earlier because of bill savings) and receive water efficiency support in terms of an audit and device installation or a leak repair before moving to a measured bill.
3	Optional, where customers opt to be billed on a measured basis, and receive water bills annually. (This option may be less effective at solving water resource challenges in the short term)

Analysis of these questions allows us to obtain an estimate of relative preferences over the three options.

Pilot Testing

Six discussion groups were undertaken with household and non household customers. This was supplemented with 12 in home interviews with customers in vulnerable circumstances and 6 telephone depth interviews with larger NHH customers.

Pilot Testing

The survey questionnaire was tested via a pilot survey of 150 customers (98 households; 52 non-households) prior to its implementation at the main stage. The pilot report was peer reviewed by Prof. Ken Willis.

Survey Administration

The survey comprised a total of 700 interviews with DCWW's customers:

- 400 with household customers and
- 300 with non-household customers.

The average interview length was 35.12 minutes for households and 28.18 minutes for non-households. All interviews were conducted using a computer-assisted telephone interviewing (CATI) method, more specifically a phone-post/email-phone approach. Fieldwork was undertaken by Accent's Telephone Unit in Edinburgh

Findings

SP1 - Water Resources Management Options

The water resources management options component of the research obtained monetary estimates of customers' willingness to pay for certain measures, and willingness to accept other measures in exchange for lower bills.

The main results from our analysis are presented in Table 2 below. Consistent with expectation, reductions in the leakage rate were found to have the biggest value to households. This was followed by the re-opening of existing unused reservoirs, new wastewater recycling works and a further bigger leakage reduction from 20% down to 15%.

For both households and non-households, a negative WTP was estimated for new river or groundwater abstractions. The biggest difference between both groups was observed for compulsory metering. While these measures come out as one of the most valued measures for non-households, households preferred them not to be undertaken, all else equal – see Table 2.

Table 2: Willingness to pay for water supply-demand measures, by customer type

Supply-demand measure	Household WTP [£/HH/year]	Non-household WTP [£/NHH/year]
Reduce leakage rate (from 22% to 20%)	£50.89	£92.98
Re-open existing unused reservoir	£37.42	£61.41
New wastewater recycling works	£26.56	£33.14
Reduce leakage rate (from 20% to 15%)	£26.31	£135.23
Water saving measures offered to targeted customers	£21.66	£39.26
Expand existing reservoir	£13.30	£57.46
Re-open existing river or groundwater abstraction	£10.44	£18.96
Internal water transfer	£9.71	£25.37
New water to neighbouring companies	£9.09	£9.09
New water transfers from neighbouring companies	£3.60	£19.38
New river or groundwater abstraction	-£4.96	-£8.57
Compulsory metering (ordinary meters)	-£10.02	£96.51
Compulsory metering (smart meters)	-£14.89	£108.41

Positive values indicate that customers would be willing to pay for the measure to be implemented, in addition to their WTP for that measure's contribution to reducing the frequency of TUBs/NEUBs. Negative figures indicate that the measure carries an external cost to customers that should be offset against their WTP for that measure's contribution to reducing the frequency of TUBs/NEUBs.

The estimates obtained from this research may be used in cost-benefit appraisals of alternative supply-demand measures for inclusion in DCWW's water resources management plan. Each value should be treated as an additional benefit, over and above the value associated with the impact of the measure in question on the frequency of a TUB/NEUB, which would offset some of the financial cost associated with implementing the measure. Inclusion of these values in cost-benefit appraisals could affect the set of options being chosen as optimal from the point of view of customers for DCWW's water resources management plan.

SP2 - Water Use Restrictions Options

The water use restrictions component of the research obtained estimates of customers' willingness to pay, in terms of increased temporary use ban duration, for having certain uses allowed rather than prohibited.

The main results from our analysis are presented in Table 3 below. The results reveal a clear pattern applicable to both customer groups with water uses relevant to a large majority of the respective property exhibiting a high WTP in the sense that respondents are willing to accept a significant extension of the duration of the hose ban to avoid restriction. Conversely, water uses only relevant to a small minority are preferred to be banned in order to shorten the duration of the TUB/NEUB.

The highest valued water use types, by households and non-households, were "Watering plants using a hosepipe" and "Clean non-domestic premises", alternatively. The water use most desired to be prohibited are "Cleaning a private leisure boat using a hosepipe" and "Filling or maintaining a non-domestic swimming pool".

Table 3: WTP for water use types to be allowed during temporary use ban at the expense of an increased duration of the ban - Households

Water use	Equivalent duration of ban (with water use shown permitted) [Months]
Watering a garden using a hosepipe	4.62
Watering plants using a hosepipe	4.51
Cleaning a private vehicle using a hosepipe	2.55
Cleaning paths, patios or outdoor surfaces using a hosepipe	0.59
Cleaning household walls or windows using a hosepipe	0.29
Cleaning other artificial outdoor surfaces using a hosepipe	-0.15
Filling or maintaining a pond using a hosepipe	-0.27
Drawing water using a hosepipe for recreational use	-0.51
Filling a swimming pool or paddling pool with a hosepipe	-1.01
Filling or maintaining an ornamental fountain	-2.07
Cleaning a private leisure boat using a hosepipe	-4.39

Positive values indicate that customers would be willing to face a longer duration of temporary use ban with the water use type to be allowed. Negative values indicate that customers would be willing to face a longer duration of ban for the water use type to be prohibited.

Table 4: WTP for water use types to be allowed during temporary use ban at the expense of an increased duration of the ban – Non-Households

Water use	Equivalent duration of ban (with water use shown permitted) [Months]
Clean non-domestic premises	19.05
Cleaning a window of a non-domestic building	10.67
Watering outdoor plants on commercial premises	7.68
Operating a mechanical vehicle-washer	6.37
Cleaning industrial plant	3.79
Suppressing dust	3.61
Cleaning any vehicle, boat, aircraft or railway rolling stock	-0.78
Filling or maintaining a pond	-0.97
Operating a cistern in any building that is unoccupied and closed	-9.68
Filling or maintaining a non-domestic swimming pool	-16.94

Positive values indicate that customers would be willing to face a longer duration of non-essential use ban for the water use type to be allowed. Negative values indicate that customers would be willing to face a longer duration of ban for the water use type to be prohibited.

The results obtained from this research may be used in cost benefit-type appraisals of alternative combinations of restrictions for inclusion in DCWW's drought plan. An economically efficient policy would involve prohibiting all the uses where the values obtained were negative, and further prohibiting uses with positive values where the value of the usage was less than the corresponding number of months of a TUB/NEUB that would likely be avoided if it were prohibited rather than allowed.

SP3 – Resilience Valuation

Results from our analysis of the SP3 exercise found that many DCWW customers attached a high value to the improvement in resilience from 1 in 100 to 1 in 200. We calculated a lower bound estimate of mean WTP for the improvement option of 5.4% of households' current bills, on average, in real terms, and 5.1% of non-households' current bills. This equates to £23.70 per household per year for households and £96.80 per year, on average, for non-households.

SP4 – Metering Options

Findings from the SP4 exercise indicated strong support amongst both households and non-households for the Progressive metering policy option (Option 2). However, households next preferred option was Optional metering (Option 3) whereas non-households' next preferred option was Compulsory metering (Option 1)

Validity Assessment

Confidence in the results presented in this report can be gained from the following:

- The vast majority of responses were assessed as valid, taking into account respondent and interviewer feedback, and the reasons respondents gave for their choices.
- Analysis of the sources of variation in WTP showed that results were consistent with expectation in many areas. There was no statistically significant coefficient found that had the opposite sign to expected whereas there were many statistically significant findings that did have the expected sign.

Conclusions

Overall, the valuation estimates presented appear to be meaningful measures of DCWW customers' values for the range of supply-demand measures contained within the survey, net of their effects on the water supply-demand balance, and for the range of water use restrictions that could be put in place to manage water resources during a drought. As such, we believe both sets of estimates are appropriate for use in cost benefit analysis for DCWW's water resources management and drought policy planning.

Furthermore, the results indicate a relatively high willingness to pay for improvements in drought resilience from a 1 in 100 chance of rota cuts to a 1 in 200 chance. The results also indicate strong customer support for the Progressive metering policy option amongst both households and non-households in comparison to compulsory and optional metering policies.

1. INTRODUCTION

1.1 Background

Dwr Cymru Welsh Water (DCWW) commissioned Accent to design and implement a quantitative willingness to pay (WTP) survey. The main aim of this study has been to provide an understanding customers' preferences in relation to the various ways of maintaining or improving the water supply-demand balance as well as with reference to the types of restrictions that might be imposed in a drought situation. A secondary task was the analysis of customer's preferences on measurements affecting the chance of a rota cut. The results provide essential insights to customers priorities and are thus to be used to both challenge and influence DCWW's water resource management plan and their drought plan.

The research is undertaken in the context of the following sources of guidance:

- Ofwat's customer engagement policy for the 2019 price review (PR19)
- UKWIR reports on "Customer involvement in price-setting", "Review of CBA and benefits valuation" and "Carrying out WTP surveys"
- experience and best practice from other sectors
- the wider academic literature on CBA and benefits valuation.

1.2 Objectives

The objectives of this research were to explore:

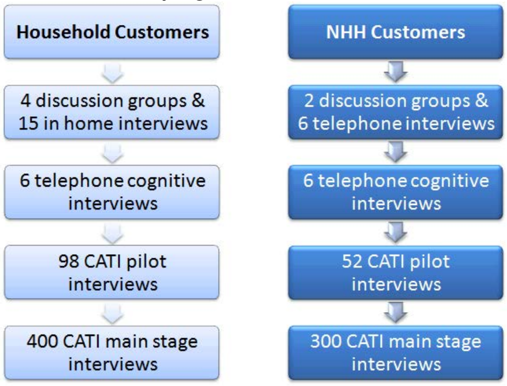
- customer preferences and WTP in relation to the different ways water resource deficits can be tackled
- attitudes towards the frequency of different types of water use restrictions
- WTP for measures that improve drought resilience and thereby reduce the risk of rota cuts
- attitudes to alternative metering policy options.

1.3 Overview of the Study

The research comprised qualitative and quantitative stages, including focus groups, in home depths, cognitive interviews, a large-scale pilot and main stage interviews. The pilot and main stage interviews were completed by an initial telephone interview, sending documents to the respondent by email or post and a follow-up telephone stated preference interview.

Figure 3 gives an overview of the research programme.

Figure 1: Overview of the research programme.



1.4 Report Structure

The remainder of this report is structured as follows. In section 2 we provide an overview of the main qualitative insights which provides context for quantitative results. In section 3, we report on the survey design and development; section 4 provides details of the survey administration; section 5 reports on aspects of the survey performance; section 6 presents the main results with respect to water resources management options; section 7 presents the main results with respect to drought water use restriction options; section 8 describes the results of the resilience analysis; section 10 presents our conclusions and recommendations.

The appendices to this report contain the questionnaires and show cards that were used in the survey (Appendix A, for households, and Appendix B for businesses). In addition, Appendix C contains details of a supplementary econometric analysis of the sources of variation in WTP.

2. OVERVIEW OF QUALITATIVE INSIGHTS

2.1 Context

An emerging segmentation evolved highlighting different types of customers when discussing resilience. The key metrics were attitude in the environment and financial security. Four segments were identified:

- **Passive** – these are cash comfortable customers who are environmentally disengaged. They have a focus on home and family and very much live in the present tense. Their environmental beliefs range from "not interested" to "just don't believe"
- **Advocates** – these are also cash comfortable customers but who are environmentally engaged. They are future focused with a strong belief in climate change. They are knowledgeable about environmental issues and have the resources and appetite to support positive environmental change
- **Oblivious** – these customers are just about managing or struggling financially and are less environmentally engaged. They are self focused on the day to day and making ends meet. They are not thinking about environment as it's not directly affecting them/not their problem
- **Supporters** – these are also just about managing or struggling financially but are environmentally engaged. Aware of environmental issues and believe that the world is changing. They feel that things need to change and think about how they can change own behaviour to benefit environment.

"I think people talk about 'climate change' but I'm not sure how much is changing because of what we do"
Passive

"I would probably support paying more for this (new infrastructure) if it was a low carbon emission scheme!"
Advocate

"It's just not something I would ever think about"
Oblivious

"I think education into our water usage would benefit us all"
Supporter

Of these groups the Advocates and Supporters have a desire to be more responsible water consumers. However, when discussing issues of resilience and water saving the majority of customers (irrespective of segment) believe it is a shared responsibility between WW and the customer. This desire to be engaged and take responsibility is something that has become evident in the PR19 engagement work and is a step change from what was observed during PR14 work where customers were generally far more passive and disengaged.

As would be expected there are a range of attitudes displayed around climate change from unfamiliar/uneducated to educated/informed:

- Unfamiliar/uneducated: climate change feels like the unknown. It's recognised as a subject but there is so much conflicting evidence. It's also impossible to predict what's going to happen and customers are unsure whether this means it's going to get wetter or drier. Basically there's just too much to think about!

"But I think the feeling is there's going to be more disruption to the way we live our lives at the moment."
Domestic, Cardiff

- Educated/informed: engaged and interested with awareness through traditional and social media channels. International events/news reports increase this awareness. In addition, children are taught about it at school. The customers are concerned about leaving a good planet and a legacy for future generations.

"My gut reaction is for the next generation we should be doing everything we can to make their ... you know my gut reaction is yeah I'm quite nice really"
SME, Cardiff

Regardless of underlying attitude to climate change, there is definitely more noise about climate change and customers believe DCWW have a duty to plan for unknown eventualities. There is no awareness of DCWW's resource plan but against the backdrop of changing climate patterns, population growth and a desire to be more responsible water consumers this plan is welcomed across the customer types.

2.2 Response to Frequency of TUBs

A small number of participants had vague memories of hosepipe bans (Summer 76, 2001) but the current plans (May to September, 1 in every 20 years) are not seen to be problematic and there is no support to change this. Feedback is that this type of measure is an inconvenience rather than anything more significant.

Customers were presented with two alternative options:

- Improving this measure to reduce the chance to 1 in 40 years. This was seen as unnecessary and a waste of DCWW's resources which could be better used elsewhere
- Decreasing this measure to increase the chance to 1 in 10 years. Some customers mentioned this spontaneously and there was some limited support. However, there were concerns about what DCWW would then do with additional resources that might be freed up by reducing the level of service in

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this particular area. On reflection there was no support for this option with most customer reluctant to opt for a service deterioration.

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~~2.2~~2.3 Response to Resilience Options

Reducing Leakage

Leaks are one of the key areas of DCWW responsibility that are visible and impact on perceptions of DCWW. Leakage portrays DCWW as careless and inefficient and feels hypocritical as consumers are encouraged to save water. It's considered bad for the environment and is wasteful and immoral. The majority of customers understand the concept of 'economic level' but feel uncomfortable with it.

"It also sticks in the throat, it's hypocritical. They're saying to us look after the water and don't waste water, and they're doing exactly that. It's hypocritical and it stinks "
Domestic, Haverfordwest

Knowing DCWW aims to 'reduce ELL as part of their plans at no cost' is crucial and demonstrates they are proactive. Within this context, there are indications that a qualitative majority would stick with current plan versus accelerating.

"It's better to address the issues when it gets to the point of economic loss and then when repairing invest in better infrastructure"
Domestic, Colwyn Bay

However, a minority feel that it's important to address all leaks, reduce any wastage and then future proof the repairs.

"It's the perception of leakage actually more than anything, it's about the fact okay yes I understand they are saying is about the fact that it becomes uneconomic, however I think basically you want to try to get down to no leak, it's still wasted water"
SME, Haverfordwest

"I just don't like the idea of leakage from an environmental point of view and I think I would rather pay a little bit more on my bill for them to address that"
Domestic, Colwyn Bay

Compulsory Metering

Response to metering is dependent on current meter status/household size/potential benefit. Most people would prefer DCWW to encourage/promote meters but leave the final choice to the customer.: Metering is a polarising topic for many:

- Business customers already have meters although micros not sure where/how this actually works. Some household customers are already on a meter (choice/non-choice) and think this is a good idea:
  - Fair to pay for usage

- Key benefit is that it might save people money
  - An important secondary benefit is that it's good for the environment
- BUT some nervousness amongst larger households, those with children:
  - Cost will go up
  - Don't want to be constantly scrutinising usage

The general consensus is that DCWW should encourage and promote metering as opposed to forcing customers to change.

"I wish they would publicise the free meter, and how much you can benefit, a lot more..my elderly neighbour, ..She didn't know about it, you know, I helped her, went online and did everything about that." SME, Haverfordwest

"It's much fairer and makes people more conscious of their usage. Smart meters are a good step forward and it means no surprises"
Domestic, Colwyn Bay

"I'm not sure I agree with metering as it can be unfair as some people pay more and it's not fair if they don't have a choice"
Domestic, Colwyn Bay

Smart technology gets people's attention and increases interest in metering. Customers are becoming more familiar with smart meters often due to experience with evolving technology from their gas/electricity suppliers and this is increasing appeal for smart water meters. Customers like the idea of being more 'in control' or 'in touch' with usage.

"I don't agree with compulsory metering but I think the smart meter is a good idea"
Domestic, Colwyn Bay
"This makes you aware of what you are using and if you know that you can do something about it"
Domestic, Colwyn Bay

There is a desire for a greater commitment from DCWW to promote smart meters.

New Infrastructure Schemes

Infrastructure initiatives seen as big capex with significant environmental ramifications.

Re-open reservoirs:

- How much would this cost?
- It sounds expensive
- Need to understand why these were closed in the first place
- What impact would this have on new wildlife and the general area

Increase capacity of reservoirs:

- Feels most logical of the three concepts

- Sounds like a lower cost than reopening/building new
- Extension vs. building
- Least impact on the environment as structures are already in place

Take more water from rivers

- Positive way to control flooding
- Very low baseline awareness of abstraction concept or laws
- After explanation, understand that DCWW are limited to how much they can take
- Some comfortable and trust DCWW to work within the guidelines
- Some more sceptical about the directives and concern about damaging ecosystems
- Unsure of storage solutions

Customers agree that it may be necessary to increase supply but none of these ideas are convincing. More information is required for a more considered assessment.

"Yeah, you've got the environment, the habitation, so you've got that to address. I think if the existing reservoirs have got the capacity to take more water, then why don't you just pump it into the existing reservoirs, you don't have to open up other disused reservoirs, so surely that would be the cheapest option "
SME, Cardiff

"Yeah so why would you want to put something in place if we're just going to do more damage to the environment by doing it."
Domestic, Haverfordwest

Recycling Wastewater

Customers like the idea of recycling wastewater as part of resilience plan but imagine this is done already. There's an increasing recycling culture and this feels like an obvious extension. Majority feel that it's important to reuse everything whenever possible. There are some concerns over drinking recycled water:

- Safety standards/regulation
- Would it taste different
- Would you know any different?

There is support for this environmentally positive scheme providing the costs aren't too high.

"Yeah just pumping in all our waste into the sea or wherever it goes is not right…anything we can do to recycle.. we have to be responsible for."
Domestic, Cardiff

"I don't believe that Welsh Water would allow us to have any water coming into our homes if that wasn't drinkable. I know they do get

problems with pipes and whatnot, but I don't think you'd suggest anything like that if it was going to be harmful. "
Domestic., Haverfordwest

"Great idea to recycle but will the drinking water taste different?"
Domestic, Colwyn Bay

Sharing & Trading

Water sharing initiatives (across Wales) are very well supported. There's a strong emotional response to water sharing that tends to override any practical concerns; customers like the idea of water sharing across Wales. Most customers feel that this is done already and don't register or know details about localised infrastructure. Customers are unsure of cost and environmental impact of laying new pipes BUT still feel this idea makes sense. Although the concept of sharing across Wales is supported, it feels like the environmental and cost impact could be significant which could dampen support.

"I think we should be able to share the water, at least within Wales?"
Domestic, Haverfordwest

"I think this should be mandatory – why aren't they doing this already?"
SME, Cardiff

Idea of raising revenue by selling to water stretched areas in England is well supported providing this is at low environmental cost. Water trading is seen as a potential revenue stream which is positive for DCWW and could enable them to invest in new infrastructure projects or reduce the cost of bills for DCWW customers.

On balance, revenue generation potential and associated positive impact on DCWW bills or projects outweighs environmental concerns for most but not all.

"We have no coal any more so this is a natural resource that we should utilise"
Vulnerable, Cardiff area

"Well, you've got to lay pipelines, or you've got to move it by rail, road, canal, whatever! But you've got to move it somehow. The cost! I don't see how you can say it would not damage the environment, because fuel, whatever is going to damage the environment. "
Domestic, Haverfordwest

"I'm not sure I'm comfortable with the idea of making a profit on this – I mean if an area in England is potentially going without water"
Domestic, Colwyn Bay

Water Saving Measures

Customers want DCWW to educate through advice *and* devices to save water. As mentioned earlier in this section there is an increased desire amongst most customer segments to become more water responsible and a desire for DCWW to help customers achieve this.

There's a sense of behavioural shift due to meters, education of children, recycling culture etc AND a shift to water consciousness – even amongst those less 'environmentally engaged'. To achieve this customers are looking for DCWW to deliver a combination of advice and devices. Advice in isolation is easy to ignore particularly amongst "passive" and "oblivious" segments. Devices are attention grabbing, again particularly so for these segments.

Kicking off the initiative with household water assessment would be most productive if this is then followed up with the offer of subsidised devices/repairs. DCWW need to keep the conversation going in an imaginative way using relevant media. There's a real opportunity for DCWW to take the lead with a forward thinking campaign to help customers effect behavioural change with their water use.

"It's very important because if you use it wisely, hopefully you will never have a problem of a shortage. It goes back to education again doesn't it and just educating the young."
SME, Haverfordwest

"Device is probably better because it's an action whereas the advice is easy to ignore"
Domestic, Colwyn Bay

3. SURVEY DESIGN AND DEVELOPMENT

3.1 Introduction

The survey design for the present study was based on addressing, via a robust stated preference survey design, the two core objectives: to research customer attitudes and WTP in relation to the different ways water resource deficits can be tackled, and to research attitudes towards the frequency of different types of water use restrictions. The choice experiment (DCE) was thus designed to focus on water resources management options. The options were characterised in this exercise by the combination of supply-demand measures included and its impact on the level of service (frequency of TUBs/NEUBs) and the customer's bill.

3.2 Questionnaire Structure

The full survey questionnaire comprised the following components.

1) Screening questions, to control sample eligibility.
2) Background questions on awareness, use of water saving devices and attitudes.
3) Background information on water supply issues in the region, current chance of a TUB/NEUB and an explanation of TUB/NEUB restrictions.
4) Questions on the types of water use the respondent engages in, when there is no TUB/NEUB in place.
5) Questions on the impact, if any, of a TUB/NEUB on the customer.
6) Contextual statement, explaining why action is needed and why customers are being consulted.
7) Information on each of the water supply-demand measures, including whether they would have a high, medium or low impact on the water balance, whether they are high, medium or low cost, and whether they have a positive, neutral or negative impact on the environment.
8) "Simple" priority questions, asking which of the water supply-demand measures they would most like to see, and least like to see implemented.
9) SP1 – water resources management exercise
10) SP2 –water use restrictions exercise
11) SP3 – resilience valuation exercise
12) SP4 – metering options exercise
13) Follow-up questions.
14) Demographics.

This structure fulfils the needs of providing the appropriate context and information for respondents to reveal their preferences, and obtaining sufficient additional data to ensure representativeness, and to test and validate the ultimate results by means of covariate analysis.

3.3 SP1 - Water Resources Management Exercise Design

The water resources management exercise (SP1) was designed on the basis that the utility of a water resources management plan, to a customer, can be decomposed into three factors:

- the impact on the frequency of TUBs/NEUBs,
- the impact on the customer's bill, and
- the external costs/benefits of the supply-demand measures included within the plan.

Starting with this premise, the exercise was designed such that respondents would be asked to make a sequence of choices between options each representing a potential water resources plan. The options were accordingly characterised by the combination of supply-demand measures included and the impact on the level of service (frequency of TUBs/NEUBs) and on the customer's bill.

Supply-Demand Measure Selection and Definition

One of the key tasks in the development of the SP survey instrument was to select and define the water supply-demand measures to be valued. The selection agreed upon was based on the options DCWW had already been appraising in developing its draft water resources management plan. The final selection of measures tested in the survey is shown in Table 5.

Table 5: Supply-demand measures tested in research

Reduce leakage • Reduce leakage (from 22% to 20%) • Reduce leakage (from 20% to 15%)
Compulsory metering • Compulsory metering (ordinary meters) • Compulsory metering (smart meters)
Reservoirs • Expand existing reservoir • Re-open existing unused reservoir
Wastewater recycling
New water transfers • New water transfers from neighbouring companies • New water transfers from neighbouring companies • New internal water transfers
Water saving measures
Additional sources of abstraction

In addition to textual descriptions, the measures were also characterised via a matrix of "impacts". These included the impacts of the measure on:

- Water available in a dry period
- The environment
- Customers bills; and
- Local disruption.

Table 7 shows the matrix using the symbols used to characterise the impacts that were used in the survey. The first measure “Reduce leakage from 22% to 20%”, for instance, would have a medium impact on the water available in a dry period, as indicated by the two water drops; a small positive impact on the environment, as shown by the single green plus sign; a medium impact on customer bills, as shown by the two pound signs and would cause a medium amount of local disruption, as shown by the two tools symbols.

Table 6: Matrix of measures and impacts

Measure	Impact on water available in a dry period	Impact on the environment	Impact on customers’ bills	Local disruption
1. Reduce leakage				
Reduce leakage (from 22% to 20%)	💧💧	+	££	⚒⚒
Reduce leakage (from 20% to 15%)	💧💧💧	++	£££	⚒⚒⚒
2. Compulsory metering				
Compulsory metering (ordinary)	💧	+	££	⚒⚒
Compulsory metering (smart)	💧💧	++	£££	⚒⚒
3. Reservoirs				
Expand existing reservoir	💧💧	--	££	⚒⚒
Re-open existing unused reservoir	💧	-	£	
4. New wastewater recycling works	💧💧💧	+	££	⚒
5. Water transfers				
New water transfers from neighbouring companies	💧💧	-	££	⚒⚒
New water transfers to neighbouring companies	💧	-	-£	⚒
New internal water transfers	💧💧	-	£	⚒
6.Water saving measures offered to targeted customers	💧	+	£	⚒
Additional sources of abstraction				
New river or groundwater abstraction	💧💧	-	£	⚒
Reinstatement of unused surface/ground water abstraction	💧💧	-	£	⚒

The more symbols shown, the greater the impact in question. In the case of “Impact on the environment”, + indicates a positive impact and - indicates a harmful impact.

Levels of Service

The TUB/NEUB chance attribute took the following levels in the survey, with Level 0 referring to the current chance of a ban.

Table 7: TUB/NEUB frequency levels

Level	Chance	
	TUB (Households)	NEUB (Non-households)
0	1 in 10 years	1 in 20 years
1	1 in 20 years	1 in 40 years
2	1 in 30 years	1 in 60 years
3	1 in 40 years	1 in 80 years

Restrictions were imposed on the experimental design to ensure that the level of service associated with a plan was correlated with the total impact of the included supply-demand measures on the water available in a dry period. This meant that, in rough terms, the more that the set of included measures as a whole impacted on the water available in a dry period for a given option, the lower the frequency of TUBs/NEUBs would be. (See below for details of the experimental design.)

Payment Vehicle Format and Levels

The bill impacts associated with each option were expressed in the same way as in the Primary WTP survey, which was itself consistent with recommendations in UKWIR (2011). Impacts were expressed in monetary terms for households and as a percentage of current bills for businesses.

The monetary amounts for households were themselves derived from a design based on percentages of current bills. At the recruitment stage of the survey, all household respondents were asked to indicate the size of their DCWW bill, if they knew it. For customers who did not know their bill, they were informed of the average annual bill for water services in the DCWW area. Accent's software then translated the percentage values from the design into monetary amounts for each household between recruitment and main interview. (Show material was posted or emailed to the respondent in the intervening period.)

The bill impact took the following levels:

Table 8: Bill impact levels

Level	Bill impact
0	Decrease of 5%
1	No change
2	Increase of 5%
3	Increase of 10%
4	Increase of 15%
5	Increase of 20%

Bill impacts refer to the total change from 2024 onwards as a percentage of respondents' current bills following five cumulative increases of equal amounts leading up to this total change.

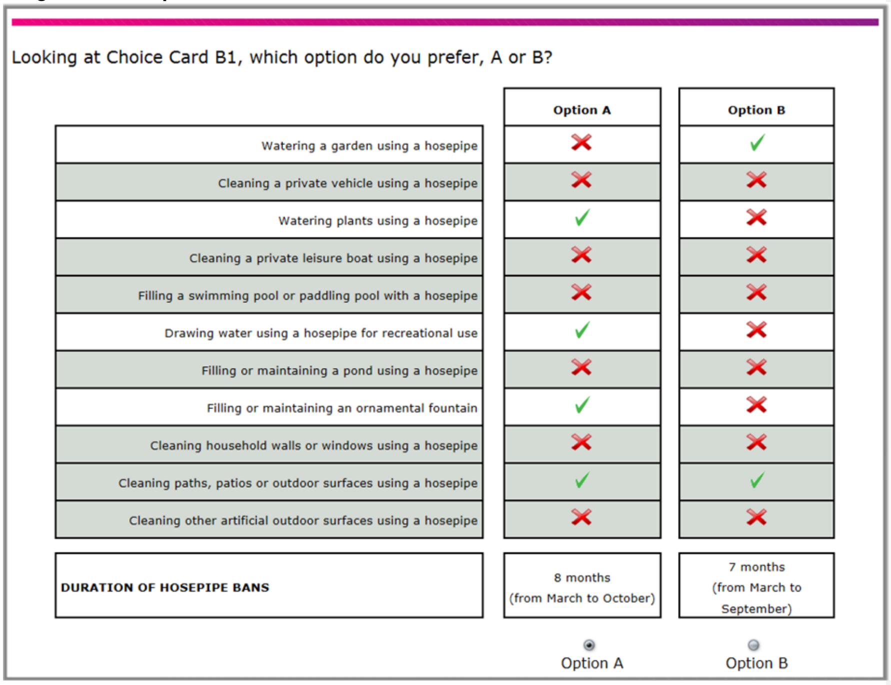
In the same way as for levels of service, restrictions were imposed on the experimental design to ensure that bill impacts shown for the options were correlated with the total bill impact of the included supply demand measures, as measured by the sum of "£" symbols over all the measures for an option. (Again, see below for details of the experimental design.)

Choice Exercise Format

The choice cards were designed with two options for respondents to choose between, each showing the combination of measures that would be included, and excluded, and, separately, the temporary use ban and bill impacts consistent with these.

Figure 4 displays an example choice card.

Figure 2: Example SP1 choice card



Looking at Choice Card B1, which option do you prefer, A or B?

	Option A	Option B
Watering a garden using a hosepipe	✗	✓
Cleaning a private vehicle using a hosepipe	✗	✗
Watering plants using a hosepipe	✓	✗
Cleaning a private leisure boat using a hosepipe	✗	✗
Filling a swimming pool or paddling pool with a hosepipe	✗	✗
Drawing water using a hosepipe for recreational use	✓	✗
Filling or maintaining a pond using a hosepipe	✗	✗
Filling or maintaining an ornamental fountain	✓	✗
Cleaning household walls or windows using a hosepipe	✗	✗
Cleaning paths, patios or outdoor surfaces using a hosepipe	✓	✓
Cleaning other artificial outdoor surfaces using a hosepipe	✗	✗
DURATION OF HOSEPIPE BANS	8 months (from March to October)	7 months (from March to September)

Option A   Option B

Experimental Design

Respondents were asked to make eight choices each in the exercise, where this number was chosen as a reasonable number balancing survey length and complexity against the statistical advantages of greater numbers of observations.

The experimental design randomly assigned each respondent one of 100 unique sequences of eight choice situations, where each of the sequences was forced to satisfy a number of imposed restrictions, discussed below. The 100 sequences were chosen as a blocked design based on the D-efficiency criterion, using pilot estimates as priors. A larger-than-usual number of blocks was chosen for this design to ensure a large amount of variation in the sample, which was felt to be necessary given the range of restrictions put in place for theoretical reasons.

The first restriction put in place on the design was that the number of attributes that differed across the two options on any one choice card was restricted to be equal to four. This approach was to make the choices significantly less complex for respondents than having up to 13 attributes varying at once. This is known as the 'partial profiles' approach in the literature. [1]

[1] Kessels, R., Jones, B., and Goos, P. (2011) Bayesian Optimal Designs for Discrete Choice Experiments with Partial Profiles, *Journal of Choice Modelling*, **4**(3), 52-74

The second issue taken account of in the experimental design is the link between measures, TUB/NEUB and bills. Clearly, the more measures that are included, the more risk reduction would be expected, and the more the impact on the bill would be. The experimental design was therefore restricted to take these links into account.

For the TUB/NEUB chance, the restrictions referred to the sum of water drop symbols over all the measures included within an option. (The maximum sum of drops possible for any option was 24.)

- Level 0 was allowed by the design only when the number of drops was less than 5
- Level 1 was allowed only when the number of drops was between 3 and 10
- Level 2 was allowed only when the number of drops was between 8 and 17
- Level 3 was allowed only when the number of drops was between 15 and 24.

Similarly, for the bill impact level, the restrictions referred to the sum of "£" symbols over all the measures for an option. (The maximum sum of "£" symbols possible for any option was 20.)

- Level 0 was allowed by the design only when the number of drops was less than 3
- Level 1 was allowed only when the number of drops was between 2 and 6
- Level 2 was allowed only when the number of drops was between 6 and 10
- Level 3 was allowed only when the number of drops was between 10 and 14
- Level 4 was allowed only when the number of drops was between 13 and 17
- Level 5 was allowed only when the number of drops was between 16 and 20
    -

The design was further restricted to exclude choice situations where there was a dominated option against an inferior alternative. We interpret this to mean cases where the chance of a TUB/NEUB and the bill are both lower in one option than the other. Finally, the design could only include ordinary or smart readers in the same option.

A similar design approach was adopted for the pilot as for the main, with the only difference being that the main stage design was calibrated to the pilot estimates according to the D-efficiency criterion.

3.4 SP2 - Water Use Restrictions Exercise Design

The water use restrictions exercise (SP2) was designed to measure customers' views on the types of water uses that should be allowed and prohibited if a hosepipe ban is put in place. In this exercise, the options that were shown were combinations of water use restrictions that would be put in place during a hosepipe ban, coupled with the expected duration of the ban that would result.

The intention in designing the exercise in this way was that it would enable the estimation of quantitative measures of customers' relative preferences between alternative water uses, measured in terms of the additional duration of the temporary use ban that would be acceptable to customers if a certain water use were allowed than if it were prohibited during the ban. The more that customers valued a particular water use, the more extra time they would be expected to be "willing to pay" to see that water use allowed rather than prohibited.

Water Use Type Selection and Definition

The potential water use restrictions tested were directly based on those listed in the Flood and Water Management Act (2010) in the case of TUBs, and on those in the Drought Direction (2011) in the case of NEUBs. These water uses also correspond to those listed in DCWW's drought plan.

Table 9 shows the water use restrictions tested in the research, by customer type.

Table 9: Water use restrictions tested in research

Households	Non-Households
Watering a garden using a hosepipe	Watering outdoor plants on commercial premises
Cleaning a private vehicle using a hosepipe	Filling or maintaining a non-domestic swimming or paddling pool
Watering plants using a hosepipe	Filling or maintaining a pond
Cleaning a private leisure boat using a hosepipe	Operating a mechanical vehicle-washer
Filling a swimming pool or paddling pool with a hosepipe	Cleaning any vehicle, boat, aircraft or railway rolling stock
Drawing water using a hosepipe for recreational use	Cleaning non-domestic premises
Filling or maintaining a pond using a hosepipe	Cleaning a window of a non-domestic building
Filling or maintaining an ornamental fountain	Cleaning industrial plant
Cleaning household walls or windows using a hosepipe	Suppressing dust
Cleaning paths, patios or outdoor surfaces using a hosepipe	Operating a cistern in any building that is unoccupied and closed.
Cleaning other artificial outdoor surfaces using a hosepipe	

Durations

The duration of the TUB/NEUB attribute took the following levels in the SP2 exercise.

Table 10: Duration of TUB / NEUB

Level	Chance
0	5 months (from May to September)
1	6 months (from April to September)
2	7 months (from March to September)
3	8 months (from March to October)

Since more restrictions would naturally be associated with shorter bans, restrictions were imposed on the experimental design to ensure that the duration associated with an option was correlated with the total number of water uses that were prohibited. This meant that, in rough terms, the more water uses that were prohibited, the shorter the duration of the temporary use ban (See below for details of the experimental design.)

Choice Exercise Format

The choice cards were designed with two options for respondents to choose between, each showing the combination of water uses that would be allowed, and not allowed, and, separately, the TUB/NEUB duration consistent with these.

Figure 5 displays an example choice card (from the household survey).

Figure 3: Example SP2 choice card

Looking at Choice Card B1, which option do you prefer, A or B?

	Option A	Option B
Watering a garden using a hosepipe	✗	✓
Cleaning a private vehicle using a hosepipe	✗	✗
Watering plants using a hosepipe	✓	✗
Cleaning a private leisure boat using a hosepipe	✗	✗
Filling a swimming pool or paddling pool with a hosepipe	✗	✗
Drawing water using a hosepipe for recreational use	✓	✗
Filling or maintaining a pond using a hosepipe	✗	✗
Filling or maintaining an ornamental fountain	✓	✗
Cleaning household walls or windows using a hosepipe	✗	✗
Cleaning paths, patios or outdoor surfaces using a hosepipe	✓	✓
Cleaning other artificial outdoor surfaces using a hosepipe	✗	✗
DURATION OF HOSEPIPE BANS	8 months (from March to October)	7 months (from March to September)

◉ Option A ○ Option B

Experimental Design

Respondents were asked to make eight choices each in the SP2 exercise, where this number was again chosen as a reasonable number balancing survey length and complexity against the statistical advantages of greater numbers of observations.

As with SP1, the experimental design randomly assigned each respondent one of 100 unique sequences of eight choice situations, where each of the sequences was forced to satisfy a number of imposed restrictions, discussed below. The 100 sequences were chosen as a blocked design based on the D-efficiency criterion, using pilot estimates as priors. A larger-than-usual number of blocks was chosen for this design to ensure a large amount of variation in the sample, which was felt to be necessary given the range of restrictions put in place for theoretical reasons.

The first restriction put in place on the design, as also done for the SP1 exercise, was that the number of attributes that differed across the two options on any one choice card was restricted to be equal to four. This approach was to make the choices significantly less complex for respondents than having up to eleven attributes varying at once.

The second issue taken account of in the experimental design was to drop dominated/dominating pairs. In the present case, Option A was determined to be dominated by Option B if the duration of the TUB/NEUB was shorter in Option B, and if all of the water uses that were allowed in Option A were also allowed in Option B. The converse rule was also held to apply in the case of Option A dominating Option B.

The third restriction on the experimental design was that the number of uses that were permitted was less than or equal to four in every option. This restriction was put in place to ensure that the options looked meaningful to respondents, and bore more than only a weak resemblance to the way that temporary use bans were described prior to the SP1 exercise, which was such that all of the uses would be prohibited.

Finally, the experimental design was restricted so that more prohibitions on water use would be associated with shorter durations. To apply this restriction:

- Level 0 was allowed only when the number of uses permitted was less than 2
- Level 1 was allowed only when the number of uses permitted was between 1 and 3
- Level 2 was allowed only when the number of uses permitted was between 1 and 3
- Level 3 was allowed only when the number of uses permitted was between 2 and 4

A similar design approach was adopted for the pilot as for the main, with the only difference being that the main stage design was calibrated to the pilot estimates according to the D-efficiency criterion.

3.5 SP3 - Resilience Valuation

The focus of the SP3 exercise was on customers' willingness to pay for an improvement in drought resilience, as measured by the expected frequency of rota cuts to supply. Specifically, respondents were first read out the context statement shown in Figure 4 below.

Figure 4: Resilience valuation context statement

Welsh Water plans its water resource strategy based on how much water it thinks it needs to supply for the next 25 years, taking into account population growth and the effects of climate change. Its plans include flexibility to allow for peaks in demand for water and changing weather patterns but not enough to rule out ever having to introduce emergency drought measures. *If these were needed, which would only happen in the case of a very severe drought of the kind experienced less than once every 100 years, water supplies to customers' properties would be limited to a few hours per day, and water would only be available at other times from standpipes in the streets.* *Welsh Water would like to strengthen the robustness and resilience of its water supply network to rule out the possibility of needing rota cuts and standpipes even in the most severe droughts. However, this would lead to an increase in each household's annual bill.*

Having read the above context statement, respondents were immediately then asked the following question:

Considering all the things you could spend your money on, would you be willing to pay an additional <CVCOST1> on your current water bill for this level of water supply security?

The variable <*CVCOST1*> in the above question was selected randomly from the set {2%,4%,8%} and multiplied by the current bill size in the case of households, or stated directly as a percentage in the case of non-households.

For those customers that said 'Yes' to this question, a follow on question asked if they would be willing to pay 2*CVCOST1. For those that said 'No' to the initial question, the follow-on question asked if they would be willing to pay 0.5*CVCOST1 for the improved level of water supply security. (This form of questioning is known in the literature as a double-bounded dichotomous choice contingent valuation exercise.)

Analysis of these questions allows us to obtain an estimate of mean WTP for the improved level of service and, in addition, an estimate of the proportion of customers that would be willing to pay any given level of bill increase between 1% and 16%. Details of the analysis methodology and full results are given in section 8.

3.6 SP4 – Metering Options

The final SP exercise in the survey related to customers' preferred choice of metering policy. Customers were given three options and asked which they would most like to see, and which they would least like to see. The options shown were the following:

Table 11: Metering options

1	A compulsory metering policy, where all customers are billed by a meter without choice. Under this scenario customers would receive information on their water use delivered via a mobile phone app, or an online account. Customers would also receive a water efficiency audit to resolve any leaks, and to install water efficiency products to help manage their water use.
2	A progressive metering policy where all customers are metered, but have a 2 year adaption period to a measured basis (unless they prefer to swap earlier because of bill savings) and receive water efficiency support in terms of an audit and device installation or a leak repair before moving to a measured bill.
3	Optional, where customers opt to be billed on a measured basis, and receive water bills annually. (This option may be less effective at solving water resource challenges in the short term)

In our analysis, we derive 'Most-Least' preference scores for the above three options by calculating the proportion of times each option was marked as 'most like to see' and subtracting from this the proportion of times the option was marked as 'least like to see'. (See Marley and Louviere, 2005, for a proof that this simple metric is a sufficient statistic for a full multinomial logit model.)

3.7 Testing and Refinement

A pilot survey was conducted prior to the main stage to test and refine the survey instrument. The overall pilot comprised a total of 150 interviews:

- 98 with household customers
- 52 with non-household customers.

All pilot interviews were conducted using a computer-assisted telephone interviewing (CATI) method. Fieldwork was undertaken by Accent's Telephone Unit in Edinburgh.

The pilot survey of household and business customers was conducted in order to test:

- the recruitment process
- the clarity and flow of the questionnaire
- the appropriateness of the language used
- the accuracy of all routings
- ease of use of the show material
- the DCE design and understanding of the DCE and contingent valuation exercises
- the interview duration
- the survey hit rate.

The performance of the survey instrument was assessed by analysing feedback from respondents, and by inspection of econometric models estimated on the pilot data.

Our findings showed the following.

- The vast majority of respondents felt able to make comparisons between the options presented to them.

- Reasons given by respondents for the choices they made in the stated preference exercises were valid, in that there were no cases of respondents incorporating invalid beliefs or inferences when making their choices.

- The econometric choice models satisfied the minimum theoretical standards for validity, in that they indicated respondents preferred better service levels to worse service levels, and preferred lower bills to higher bills, all else equal. Moreover, the levels of precision were reasonably good for the sizes of the pilot samples used in the analysis.

In light of these findings, and following a supportive peer review from Prof. Ken Willis, the pilot survey instrument was adopted for the main stage of the survey as planned.

4. SURVEY ADMINISTRATION

The main stage comprised a total of 700 interviews with DCWW's customers:

- 400 with household customers and
- 300 with non-household customers.

Interview Length

The average interview length was 35.12 minutes for households and 28.18 minutes for non-households.

Sampling and Recruitment Method

The sample for the household survey was sourced by Accent, ensuring that a representative sample of the population participated in the survey. The sample for the non-household survey was provided by DCWW and comprised 250 customers with dual supply and 50 customers with water supply only. Customers' postcodes were checked against a lookup list to verify their supply area, and followed up with a question for participants to confirm their water and sewerage suppliers.

Household Survey

The household interviews were conducted using a computer-assisted telephone interviewing (CATI) method, more specifically a phone-post/email-phone approach. Fieldwork was undertaken by Accent's Telephone Unit in Edinburgh.

The final breakdown of supply areas achieved in the household survey is shown in Table 12 below.

Table 12: Supply areas

	Frequency
Welsh Water supplies water and sewerage	362
Welsh Water supplies water, another company (Wessex Water) provides sewerage	38
Total	**400**

To achieve 400 completed interviews, 734 customers were recruited.

Non-household survey

Non-household interviews were conducted using a computer-assisted telephone interviewing (CATI) method, more specifically a phone-post/email-phone approach. Fieldwork was undertaken by Accent's Telephone Unit in Edinburgh.

To achieve 300 completed interviews, 677 customers were recruited.

Sample Characteristics

Household

The breakdown of household interviews is shown in Table 13 below.

Table 13: Household sample characteristics

Characteristic	Value	Frequency
Gender	Male	166
	Female	234
Age	18-34	35
	35-64	212
	65-74	80
	75 or older	61
	Prefer not to say	12
SEG	A/B	134
	C1/C2	166
	D/E	94
	Prefer not to say	6
Water meter status	Water meter	143
	No water meter	255
	Don't know	2
Working status	Working full-time (30+ hours a week)	142
	Working part-time (8-29 hours a week)	40
	Not working – looking for work	7
	Not working – not looking for work	13
	Full-time student	2
	Part-time stuent	1
	Retired	162
	Retired unpaid voluntary work	8
	Looking after family/home	15
	Other	10
Highest level of qualifications[2]	No qualifications	36
	Level 1	39
	Level 2	64
	Apprenticeship	5
	Level 3	55
	Level 4 and above	180
	Other qualifications	18
	Prefer not to say	3
Benefits	Attendance Allowance	18
	Carer's Allowance	19
	Child Tax Credit	45
	Council Tax Benefit	35
	Disability Living Allowance	38
	Housing Benefits	29
	Income Support (or similar)	14
	Jobseeker's Allowance	4
	Pension Credit	15
	Universal Credit	1
	Working Tax Credit	14
	None of these	280
	Prefer not to say	5
Property type	Flat	17

[2] **Level 1:** 1-4 O Levels/CSE/GCSEs (any grades), Entry Level, Foundation Diploma, NVQ Level 1,Foundation GNVQ, Basic/Essential Skills; **Level 2:** 5+ O Level (Passes)/CSEs (Grade 1)/GCSEs (Grades A*-C), School Certificate, 1 A Level/ 2-3 AS Levels/VCEs, Intermediate/Higher Diploma, Welsh Baccalaureate Intermediate Diploma, NVQ level 2, Intermediate GNVQ, City and Guilds Craft, BTEC First/General Diploma, RSA Diploma; **Level 3:** 2+ A Levels/VCEs, 4+ AS Levels, Higher School Certificate, Progression/Advanced Diploma, Welsh Baccalaureate Advanced Diploma, NVQ Level 3; Advanced GNVQ, City and Guilds Advanced Craft, ONC, OND, BTEC National, RSA Advanced Diploma; **Level 4** and above: Degree (for example BA, BSc), Higher Degree (for example MA, PhD, PGCE), NVQ Level 4-5, HNC, HND, RSA Higher Diploma, BTEC Higher level, Foundation degree (NI), Professional qualifications (for example teaching, nursing, accountancy); **Other qualifications:** Vocational/Work-related Qualifications, Foreign Qualifications (not stated/level unknown)

	Terraced house	94
	Semi-detached house	107
	Detached house	130
	Bungalow	51
	Prefer not to say	1
	Total	**400**

Non-household

Table 14 shows the breakdown of non-household interviews by bill size, annual water consumption, number of sites operated from, number of employees, core business activity and water meter status.

Table 14: Non-household sample characteristics

Characteristic	Value	Frequency
Bill size	Dual usage – small (less than £1,000)	164
	Dual usage – medium (£1,000-19,999)	74
	Dual usage – large (£20,000+)	12
	Water only – small	24
	Water only – medium	25
	Water only – large	1
Annual water consumption	>5 Ml	188
	<5Ml	10
	Don't know	102
Number of sites	1	234
	2	26
	3	11
	4+	29
Number of employees	None, sole trader	70
	Less than 4	76
	4 to 49	121
	50 to 249	17
	250+	16
Business sector	Agriculture, forestry and fishing	26
	Mining and Quarry	1
	Manufacturing	16
	Construction	12
	Wholesale and retail trade (include motor vehicles repair)	44
	Transport and storage	9
	Hotels and catering	33
	IT and communication	7
	Finance and insurance activities (incl real estate activities)	17
	Business services	21
	Government, health & education	49
	Arts, entertainment and recreation	35
	Other service activities	17
	Other	13
Water Meter Status	Water meter	208
	No water meter	69
	Don't know	23
	Total	**300**

Survey Enjoyment

All participants were asked to rate their enjoyment in completing the questionnaire using a scale of 1 to 10 where 1 means 'low enjoyment' and 10 means 'high enjoyment'.

Table 15 shows mean ratings given by participants by survey type.

Table 15: Survey enjoyment mean ratings

Survey enjoyment	Household	Non-household
Mean rating	7.35	6.53
Base size	400	300

5. SURVEY PERFORMANCE

The SP elements of the survey were potentially quite complex, particularly in the case of SP1 which included many measures that could have been unfamiliar to respondents. It was therefore important to carry out validity checks on respondents' understanding and ability to make comparisons.

Following each of the SP1 and SP2 choice exercises, respondents were asked if they felt able to make comparisons between the two options that were presented to them in that exercise. Respondents fed back positively on the survey itself as shown in Table 12.

Table 16: Respondents' perceived ability to make comparisons between options, by choice exercise and customer type

		SP1	SP2
Households	Able to compare between options	84.5&	88.5%
	Struggled to compare between the options	15.5%	11.5%
Non-Households	Able to compare between options	85.7	90%
	Struggled to compare between the options	14.3%	10%

Base: All respondents – Household: 400 (unweighted); Non-Households: 300 (unweighted)

The vast majority of respondents stated that they felt able to compare between the options presented to them across each of the two exercises and customer types. These figures are good for a stated preference survey such as this, and as such provide evidence to support the validity of the main results.

6. SP1 FINDINGS - WATER RESOURCES MANAGEMENT

6.1 Introduction

The first choice exercise (SP1) asked respondents to choose between alternative water resources management plans with each alternative being characterised by a specific combination of water supply-demand measures, their impact on the frequency of TUBs/NEUBs, and the impact on the size of the water bill. The main results presented in this section are all obtained via econometric analysis of the responses to these questions.

In this section, we begin in 6.2 by providing an overview of our analysis methodology. Section 6.3 presents the main econometric models followed by the main WTP results in section 6.4. Finally, section 6.5 summarises the results from a supplementary econometric analysis of the sources of WTP variation, which is used to support a validity appraisal of the results by testing that WTP varies in line with expectation. The econometric analysis is reported on in detail in Appendix C.

6.2 Analysis Methodology

The data from the SP1 exercise, for both households and non-households, consisted in a sequence of eight choices per respondent, each between two alternatives.[3] Choices are interpreted in our analysis as indicating that the utility of the chosen option is greater than the utility of the non-chosen option. This interpretation follows the principles of random utility theory (see e.g. Train, 2003).

The alternatives shown to respondents were generic, i.e. there were no systematic differences between Option A and Option B; this approach assumes a common utility specification for both alternatives with no alternative specific constants. Thus, the utility of an option for a respondent is modelled as being comprised of a component that depends deterministically on the levels of the attributes and a second component that presents the respondents' unobserved preferences. For the purpose of estimation, the latter is assumed to be randomly distributed.

Table 13 describes the variables used in the analysis. All of the supply-demand measures variables are represented by dummy variables equal to one if the measure was included in the plan and equal to zero if not. Additionally, the frequency of TUBs/NEUBs was represented by a continuous variable, *hose*, equal to the chance per year of a ban.

As presented in Table 13, the *hose* variable takes different values for households and non-households as restrictions on domestic properties have a higher chance of being imposed than restrains on commercial organisations. The variable *bigimp_hose* was defined as the interaction between *hose* and a dummy variable that took the value of

[3] For the purposes of analysis, the data were organised in a manner that an observation represented an individual option; hence for *N* respondents in the sample, there would potentially be *N**8*2 = 16*N* observations in each model, providing none were excluded. All analyses were conducted using the Stata software package.

one if respondents confirmed that a hosepipe ban would have a significant impact on their household or business. Finally, the bill impact of an option is represented by the continuous variable *bill*, which is measured as the number of percentage points different from the current bill.

Table 17: Variables used in SP1 analysis

Variable name	Description	Values taken by variable
leakage20	Reduce leakage (from 22% to 20%)	{1='Yes'; 0='No'}
leakage15	Reduce leakage from (20% to 15%)	{1='Yes'; 0='No'}
meterord	Compulsory metering (ordinary)	{1='Yes'; 0='No'}
metersmart	Compulsory metering (smart)	{1='Yes'; 0='No'}
resexpand	Expand existing reservoir	{1='Yes'; 0='No'}
resreopen	Re-open existing unused reservoir	{1='Yes'; 0='No'}
recycle	New wastewater recycling works	{1='Yes'; 0='No'}
transfers_from	New water transfers from neighboring companies	{1='Yes'; 0='No'}
transfers_to	New water transfers to neighboring companies	{1='Yes'; 0='No'}
transfers_within	New internal water transfers	{1='Yes'; 0='No'}
wsmeasures	Water saving measures offered to all customers	{1='Yes'; 0='No'}
abstractnew	New river or groundwater abstraction	{1='Yes'; 0='No'}
abstractreoopen	Reinstatement of unused surface/ground water abstraction	{1='Yes'; 0='No'}
hose (HH)	Frequency of temporary use bans (TUB)	{1/10; 1/20; 1/30; 1/40}
hose (NHH)	Frequency of non-essential use bans (NEUB)	{1/20; 1/40; 1/60; 1/80}
bigimp_hose	Frequency of TUB/NEUB for respondents confirming a major impact on their property	*See hose*
bill	Percentage change in respondents' water bill	{-5; 0; 5; 10; 15; 20}

Our principal model for obtaining WTP results was specified such that the utility of an option was as follows

$$(7.1)\quad U_{ijt} = \beta_1 leakage20_{ijt} + \beta_2\ leakage15_{ijt} + \beta_3 meterord_{ijt} + \beta_4 metersmart_{ijt} + \beta_5 resexpand_{ijt} + \beta_6 resreopen_{ijt} + \beta_7 recycle_{ijt} + \beta_8 transfers\_from_{ijt} + \beta_9 transfers\_to_{ijt} + \beta_{10} transfers\_within_{ijt} + \beta_{11} wsmeasures_{ijt} + \beta_{12} abstractnew_{ijt} + \beta_{13} abstractreoopen_{ijt} + \beta_{14} bigimp\_hose_{ijt} + \gamma bill_{ijt} + \varepsilon_{ijt}$$

In equation (7.1), U_{ijt} indicates the utility associated with Option *j* for respondent *i* on choice occasion *t*. The model then includes a variable representing each measure, a variable representing the risk of a temporary use ban and a variable representing the bill impact of the option. All of the variables enter the utility function linearly with parameters $\beta_1, \beta_2, ..., \beta_{11}$ and γ . Finally, ε_{ijt} is a random error term.

The variable *bigimp_hose* was included in preference to, and in place of, *hose*, due to the fact that in preliminary testing the coefficient on *hose* was positive, suggesting that customers preferred more frequent hosepipe bans to less frequent bans, all else equal. Our approach in light of this finding was to include only the variable *bigimp_hose* and exclude the *hose* variable, an approach which effectively restricted the marginal utility of hosepipe ban frequency to be zero for those saying hosepipe bans would have a less than big impact on them, and estimating the impact only for those who said hosepipe bans would have a big impact on them. This approach ensured that the resulting model contained theoretically reasonable coefficients.

Each of the econometric models was estimated as a panel mixed logit model (Revelt and Train, 1998). The panel mixed logit modelling approach requires making two further assumptions: firstly, that the error term is independently and identically distributed according to the Extreme Value distribution, and secondly that the β parameters are distributed according to a specified family, to be decided by the analyst. In our analysis, we have assumed that each parameter, except γ, has a normal distribution in the population, and that γ is treated as being fixed.

Importantly, the marginal utility estimates (β_k parameters) have only meaning in this type of model as indicators of preference in relation to one another and not in absolute terms. The ratio of (minus) each β parameter to γ indicates the mean, and median, WTP for a change of 1 unit in the variable corresponding to the β parameter, holding all other variables constant.

The WTP values obtained from this model for the supply-demand measures hold the frequency of TUB/NEUB constant, and so can be interpreted as the 'external' cost or benefit of the measure, after accounting for the direct value of the measure's impact on the chance of a TUB/NEUB. In principle, the values could be positive or negative, depending on whether the external effects on customers are themselves considered positively or negatively. Positive values would indicate that customers are willing to pay for the measure to be implemented, in addition to their WTP for that measure's contribution to the reduced need for TUBs/NEUBs. Negative figures would indicate that the measure carries an external cost to customers that should be offset against their WTP for that measure's contribution to the reduced need for TUBs/NEUBs.

6.3 Econometric Models

Households

Table 14 shows the main results for the household model. The coefficients can be interpreted as marginal utilities; a positive sign suggests therefore that the service was favourably valued by the average respondent whereas a negative coefficient implies that respondents perceived the service as undesirable.

The results in Table 14 show that the model fits the data well. Out of 13 measures, nine pass for statistical significance at 10% or better. The two variables that carried a strong theoretical prior, *bigimp_hose* and *bill*, both enter the models with the expected negative sign signifying that respondents preferred a lower bill and a reduced risk of a hosepipe ban, all else equal. As described above, *bigimp_hose* screens out respondents who felt that a hosepipe ban would have a less than big impact on them making the result and its magnitude highly plausible. There were no theoretical priors for the other variables as they could conceivably have been considered either positively or negatively by respondents.

The results in Table 14 show a negative coefficient for either form of metering, and for the additional abstraction of river or groundwater. This suggests that households would prefer that those measures were not undertaken, all else equal. For all other supply-demand measure variables, the positive coefficient indicates that household customers valued them in excess of their contribution to the frequency of TUBs.

Table 18: Main SP1 model results - households

Variable	Mean (Coef, Std. error)		Std. deviation (Coef, Std. error)	
leakage20	0.855	(0.125)***	0.850	(0.236)***
leakage15	0.429	(0.125)***	0.636	(0.288)**
meterord	-0.165	(0.116)	1.025	(0.168)***
metersmart	-0.236	(0.136)*	1.041	(0.195)***
resexpand	0.189	(0.090)**	0.472	(0.183)***
resreopen	0.606	(0.092)***	0.489	(0.207)**
recycle	0.420	(0.096)***	0.538	(0.185)***
Transfers_from	0.095	(0.094)	0.348	(0.166)**
Transfers_to	0.134	(0.086)	0.451	(0.176)***
Transfers_within	0.175	(0.081)**	0.302	(0.231)
wsmeasures	0.412	(0.086)***	0.526	(0.173)***
abstractnew	-0.104	(0.083)	0.331	(0.173)*
abstractreoopen	0.158	(0.083)*	0.566	(0.178)***
bigimp_hose	-25.579	(18.548)	47.096	(22.105)**
bill	-7.263	(1.601)***		
No. observations (=N*8*2)	6,400			
LL	-2087.408			
Pseudo R^2	0.069			

Estimated model = mixed logit, assuming normal distributions for all variables except bill*, which was treated as fixed. Dependent variable for model = choice, a {0,1} dummy variable indicating that the option was chosen. Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%. Variables are as defined in Table 13. The "LL" value shows the log likelihood of the model at convergence.*

Non-Households

Table 14 shows the main model results for non-households. The values for the measures reach similar significance as for households. The results are also mainly positive, with only *abstractnew* measured with a negative value. In contrast to households, *meterord* and *metersmart* are this time among the highest values, which indicates that non-households are much more supportive of compulsory metering than households overall.

An important difference in comparison to the household model is the exclusion of the *bigimp_hose*. The decision to have the variable excluded was made after previous tests of the original model reported a positive coefficient for both *hose* and *bigimp_hose*. This suggests that respondents would prefer more NEUBs, all else equal, even where they said that an NEUB would have a big impact on them. This finding is unreasonable on theoretical grounds as the basis of a model and so was restricted out. The ultimate model thus embeds the restriction that the value of reducing the frequency of NEUBs is zero overall for non-households.

Table 19: Main SP1 model results – Non-households

Variable	Mean (Coef, Std. error)	Std. deviation (Coef, Std. error)
leakage20	0.663 (0.144)***	0.741 (0.316)**
leakage15	0.964 (0.186)***	1.400 (0.272)***
meterord	0.688 (0.140)***	0.537 (0.355)
metersmart	0.773 (0.177)***	1.207 (0.236)***
resexpand	0.410 (0.107)***	0.158 (0.254)
resreopen	0.438 (0.129)***	1.135 (0.222)***
recycle	0.236 (0.131)*	0.949 (0.220)***
Transfers_from	0.138 (0.111)	0.191 (0.231)
Transfers_to	0.065 (0.107)	0.547 (0.205)***
Transfers_within	0.181 (0.098)*	0.014 (0.203)
wsmeasures	0.280 (0.108)***	0.843 (0.202)***
abstractnew	-0.061 (0.095)	0.023 (0.194)
Abstractreoopen	0.135 (0.097)	0.463 (0.238)*
Bill	-13.473 (2.057)***	
No. observations (=N*8*2)	4.800	
LL	-1560.237	
Pseudo R^2	0.066	

Estimated model = mixed logit, assuming normal distributions for all variables except bill*, which was treated as fixed. Dependent variable for model = choice, a {0,1} dummy variable indicating that the option was chosen. Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%. Variables are as defined in Table 13. The "LL" value shows the log likelihood of the model at convergence.*

6.4 Willingness to Pay Findings

WTP for Supply-Demand Measures

Table 20 shows the results of the above models transformed into WTP by dividing each coefficient by the negative coefficient of *bill*. The results are also graphically depicted in Figure 5.

The values show how much the average household and non-household would be prepared to pay in addition to their current annual water bill to fund the respective service improvement. ~~–~~Negative numbers indicate the level of compensation they would need in the form of a lower bill in return for the implementation of the corresponding measure.

In general, the WTP values are higher than anticipated based on previous results in the analysis for the PR14. The observed "increase" in the WTP is ultimately driven by a significantly higher value for an avoided TUB in PR19 (£228/HH) than measured in the study for the PR14 (£34). Consistently, measures designed to reduce the chance of a temporary use ban are valued higher than in the last research.

The order of priorities is largely consistent with expectations in that a reduction in the leakage rate from 22% to 20% had the biggest value to households followed by the re-opening of existing unused reservoirs, new waste water works and a further bigger leakage reduction from 20% down to 15%.

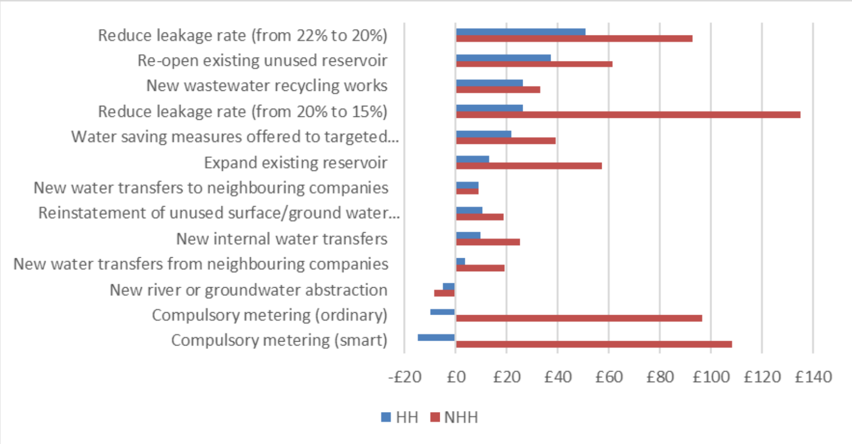
Compulsory metering and new river or groundwater abstraction had negative WTP values for households, indicating that they would prefer them not to be undertaken, all else equal. By contrast, compulsory metering was one of the most valued measures for non-households together with leakage reductions. Consisted across both types of customers was the negative WTP for new river or groundwater abstractions.

Table 20: SP1 willingness to pay results

Variable	Households [£/HH/year]	Non-Households [£/NHH/year]
Reduce leakage rate (from 22% to 20%)	£50.89	£92.98
Reduce leakage rate (from 20% to 15%)	£26.31	£135.23
Compulsory metering (ordinary meters)	-£10.02	£96.51
Compulsory metering (smart meters)	-£14.89	£108.41
Expand existing reservoir	£13.30	£57.46
Re-open existing unused reservoir	£37.42	£61.41
New wastewater recycling works	£26.56	£33.14
New water transfers from neighbouring companies	£3.60	£19.38
New water to neighbouring companies	£9.09	£9.09
Internal water transfer	£9.71	£25.37
Water saving measures offered to targeted customers	£21.66	£39.26
New river or groundwater abstraction	-£4.96	-£8.57
Re-open existing river or groundwater abstraction	£10.44	£18.96

Results derived from the models shown in Table 14 and Table 15 by dividing the coefficient of each variable by minus the coefficient on bill.. *Variables are as defined in Table 13.*

Figure 5: Willingness to pay for water supply-demand measures by customer type



Source of WTP estimates: Table 16. Positive values indicate that customers would be willing to pay for the measure to be implemented, in addition to their WTP for that measure's contribution to the water supply-demand balance. Negative figures indicate that the measure carries an external cost to customers that should be offset against their WTP for that measure's contribution to the water supply-demand balance.

WTP for Improved Levels of Service

Table 17 shows the results regarding households' WTP for a reduction in the frequency of TUBs. The results are not statistically significant at the 10% level of significance, which indicates that the hypothesis of zero WTP for reductions in the frequency of TUBs cannot be rejected at the 10% level of significance. Nonetheless, the best estimate is that there is some positive WTP for improvements in the levels of service.

Table 21: Willingness to pay for improved levels of service

Level of service change	WTP (£/HH/year)
Frequency of temporary use bans	
Base (1 in 20) to +1 (1 in 30)	0.41
Base (1 in 20) to +2 (1 in 40)	0.62

The results in Table 17 show that customers were willing to pay £0.41 per year on top of their current bills, on average, for a reduction in the chance of a TUB from 1 in 20 to 1 in 30, and were willing to pay £0.62 per year, on average, for a reduction in the chance of a TUB from 1 in20 to 1in 40.

6.5 Analysis of WTP Variation

An important test of the validity of the WTP results from an SP survey concerns analysing the extent to which WTP varies in line with expectation (Bateman et al. 2002). In Appendix C we report on an econometric analysis of the determinants of choice, and WTP, variation which performs this test.

In summary, we test the following hypotheses:

- Responses given to the choice exercise should be consistent with the responses to the earlier “simple priority” questions in the survey, which asked respondents to choose their preferred measures for inclusion in DCWW’s plan, and the measures they would least like to see implemented.
- Respondents saying their current bill was “Slightly too much” or “Far too much” should be more cost sensitive than other respondents.
- Respondents on a metered tariff should be relatively less averse to compulsory metering than other households. This is because households that are currently unmetered would presumably prefer to retain the option over whether to switch to a meter or not, rather than it be made compulsory, whereas this option has no value for households already on a metered tariff.

The results from our econometric analysis, reported in full in Appendix C. Overall, the findings are fully supportive of the validity of the results. There were many statistically significant findings that had the expected sign, and no anomalous results.

7. SP2 FINDINGS - WATER USE RESTRICTIONS

7.1 Introduction

The second choice exercise (SP2) focused on respondents' preferences between alternative forms of TUB/NEUB, which contained varying combinations of water use restrictions and ban durations. The main results from this study in respect of water use restriction preferences are obtained via an econometric analysis of responses to these DCE questions.

Our approach to analysis of the SP2 responses consisted of the following steps:

- estimating econometric models to explain respondents' choices;
- calculating willingness to pay for having each type of usage allowed (given a selection of other uses prohibited) in terms of the additional duration of temporary use bans that would be acceptable;
- exploring the extent to which this WTP varied in line with expectation via an econometric analysis of the sources of variation.

In this section, we begin by providing an overview of our SP2 analysis methodology (7.2). Section 7.3 presents the main econometric models. Section 7.4then presents our main WTP results.

7.2 Analysis Methodology

The data from the 'Water use restrictions' exercise (SP2), for both households and businesses, consisted in a sequence of eight choices per respondent, each between two generic alternatives.[4] As in the SP1 analysis, choices are interpreted as indicating that the utility of the chosen option is greater than the utility of the non-chosen option, and a common utility specification was assumed for both alternatives that included a deterministic component and a random component.

Table 17 describes the variables used in the SP2 analysis. All of the water use types are represented by dummy variables equal to one if the water use is allowed in the option, and equal to zero if not. Additionally, the duration of temporary use bans is represented by a continuous variable, *duration*, equal to the number of months that the typical temporary use ban would last, given the water uses allowed and not allowed in the option.

[4] For the purposes of analysis, which was conducted using the Stata software package, the data were organised so that an observation represented an individual option, so that for *N* respondents in the sample, there would potentially be *N**8*2 = 16*N* observations in each model, providing none were excluded.

Table 22: Variables used in SP2 analysis

Customer group	Variable name	Description	Values taken by variable
Households	*garden*	Watering a garden using a hosepipe	{1='Allowed'; 0='Not allowed'}
	vehicle	Cleaning a private vehicle using a hosepipe	{1='Allowed'; 0='Not allowed'}
	plants	Watering plants using a hosepipe	{1='Allowed'; 0='Not allowed'}
	boat	Cleaning a private leisure boat using a hosepipe	{1='Allowed'; 0='Not allowed'}
	pool	Filling a swimming pool or paddling pool with a hosepipe	{1='Allowed'; 0='Not allowed'}
	recreation	Drawing water using a hosepipe for recreational use	{1='Allowed'; 0='Not allowed'}
	ponds	Filling or maintaining a pond using a hosepipe	{1='Allowed'; 0='Not allowed'}
	fountain	Filling or maintaining an ornamental fountain	{1='Allowed'; 0='Not allowed'}
	walls	Cleaning household walls or windows using a hosepipe	{1='Allowed'; 0='Not allowed'}
	paths	Cleaning paths, patios or outdoor surfaces using a hosepipe	{1='Allowed'; 0='Not allowed'}
	surfaces	Cleaning other artificial outdoor surfaces using a hosepipe	{1='Allowed'; 0='Not allowed'}
	duration	Duration of temporary use ban [months]	{5, 6, 7, 8}
Non-Households	*plants*	Watering outdoor plants on commercial premises	{1='Allowed'; 0='Not allowed'}
	pool	Filling or maintaining a non-domestic swimming or paddling pool	{1='Allowed'; 0='Not allowed'}
	pond	Filling or maintaining a pond	{1='Allowed'; 0='Not allowed'}
	mechwasher	Operating a mechanical vehicle-washer	{1='Allowed'; 0='Not allowed'}
	vehicle	Cleaning any vehicle, boat, aircraft or railway rolling stock	{1='Allowed'; 0='Not allowed'}
	premises	Cleaning non-domestic premises	{1='Allowed'; 0='Not allowed'}
	window	Cleaning a window of a non-domestic building	{1='Allowed'; 0='Not allowed'}
	machinery	Cleaning industrial plant	{1='Allowed'; 0='Not allowed'}
	dust	Suppressing dust	{1='Allowed'; 0='Not allowed'}
	closed	Operating a cistern in any building that is unoccupied and closed.	{1='Allowed'; 0='Not allowed'}
	duration	Duration of non-essential use ban	{5, 6, 7, 8}

Analogue to the approach described in chapter 6.2, the model for obtaining WTP results was specified as follows (example Households)

(8.1) $$U_{ijt} = \beta_1 garden_{ijt} + \beta_2 vehicle_{ijt} + \beta_3 plants_{ijt} + \beta_4 boat_{ijt} + \beta_5 pool_{ijt} + \beta_6 recreation_{ijt} + \beta_7 ponds_{ijt} + \beta_8 fountain_{ijt} + \beta_9 walls_{ijt} + \beta_{10} paths_{ijt} + \beta_{11} paths_{ijt} + \gamma duration_{ijt} + \varepsilon_{ijt}$$

In equation (8.1), U_{ijt} indicates the utility associated with Option *j* for respondent *i* on choice occasion *t*. All of the variables from Table 17 entered the utility function linearly with parameters $\beta_1, \beta_2, ..., \beta_{11}$ and γ . Finally, ε_{ijt} is a random error term.

As in the SP1 analysis, each of the econometric models was estimated as a panel mixed logit model (Revelt and Train, 1998). In our SP2 analysis we have assumed that each parameter, except γ, has a normal distribution in the population, and that γ is fixed. These assumptions are consistent with the approach taken in the SP1 analysis.

The marginal utility estimates (β_k parameters) have meaning in this model as indicators of preference only in relation to one another, and not in absolute terms. The ratio of (minus) each β parameter to γ indicates the mean, and median, WTP, measured in terms of temporary use ban duration, for a change of 1 unit in the variable corresponding to the β parameter, holding all other variables constant.

Consistent with this definition, WTP is measured here in units of months of TUB/NEUB duration. For instance, $-\beta_{1/}\ \gamma$ equals the mean number of months longer that a TUB could be, with "Watering a garden using a hosepipe" allowed, before customers would prefer that it were prohibited as part of the TUB. Likewise, $-\beta_{2/}\ \gamma$ equals the mean number of months longer that a TUB could be, with "Cleaning a private vehicle using a hosepipe" allowed, before customers would prefer that it were prohibited as part of the TUB; and so on.

As in the analysis of the water resource management choices (SP1), the WTP values could be positive or negative. Positive WTP values indicate that customers are willing to have a longer ban if the measure is allowed than if it is prohibited. Conversely, a negative WTP value suggests that customers are willing to have a longer ban if the measure is prohibited than if it is allowed. A negative WTP can be interpreted in the sense that customers have preferences what we as a society are allowed to do, preferring that certain uses won't be allowed if water use is being restricted.

The WTP values for each water use were obtained on the basis that all other water uses remained fixed. Thus, the WTP value reflects the increased duration of a TUB/NEUB that is acceptable to customers on the basis that all other prohibitions previously in place would remain in place and no new prohibitions will be added to substitute for the specific water use type now being made allowable. Furthermore, each WTP value is to be interpreted as being applicable for all possible combinations of allowances and prohibitions with respect to the other water use types. That is, no specific baseline is set in terms of which uses are allowed or prohibited.

7.3 Econometric Models

Households

Table 18 shows the SP2 model results for households. The model included variables representing each water use and a variable representing the duration of the ban associated with the option, as defined in Table 17. The coefficients are to be interpreted as marginal utilities; a positive sign indicates that respondents would like the water use type to be allowed and a negative sign means that they would prefer it to be prohibited.

The model shown in Table 18 fits the data reasonably well. Six out of eleven variables pass for statistical significance at 5% or higher. As expected, *duration* enters the models with a negative sign that is statistically significant at the 1% level thereby confirming that people prefer shorter temporary use bans, all else equal.

The number of attributes with a negative coefficient are larger than those with a positive value. By implication, respondents are not only concerned about which activities are permitted during the period of a drought but also what activities ought to be banned.

Table 23: Main SP2 model results – households

Variable	Mean (Coef, Std. error)	Std. deviation (Coef, Std. error)
garden	1.035 (0.137)***	1.240 (0.160)***
vehicle	0.572 (0.112)***	1.016 (0.190)***
plants	1.010 (0.130)***	1.340 (0.189)***
boat	-0.983 (0.121)***	1.078 (0.160)***
pool	-0.226 (0.111)**	0.976 (0.179)***
recreation	-0.114 (0.105)	-0.622 (0.174)***
ponds	-0.059 (0.103)	0.708 (0.167)***
fountain	-0.463 (0.108)***	0.800 (0.174)***
walls	0.065 (0.099)	-0.040 (0.357)
paths	0.132 (0.101)	-0.362 (0.223)
surfaces	-0.033 (0.109)	-0.865 (0.168)***
duration	-0.224 (0.068)***	
No. observations (=N*8*2)	6,400	
LL	-1965.943	
Pseudo R^2	0.128	

*Estimated model = mixed logit, assuming normal distributions for all variables except for duration which was fixed. Dependent variable for model = choice, a {0,1} dummy variable indicating that the option was chosen. Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%. Variables are as defined in Table 17. The "LL" value shows the log likelihood of the model at convergence.*

Non-Households

The model results for non-households are displayed in Table 19 with similar outcome as for households; six out of ten variables pass for statistical significance at 10% level or higher. The coefficient on *duration* is negative, as expected, but is not statistically significant at the 10% level. With duration being the "paying vehicle", that is the WTP results from the division of the respective measure by *duration*, this raises some concerns regarding the accuracy of the estimated WTP. As for households, there is a considerable number of attributes with a negative coefficient though the ratio is in favour of uses that ought to be permitted during a drought period.

Table 24: Main SP2 model results – non-households

Variable	Mean (Coef, Std. error)	Std. deviation (Coef, Std. error)
plants	0.207 (0.102)**	-0.378 (0.310)
pool	-0.457 (0.125)***	1.123 (0.174)***
pond	-0.026 (0.109)	0.835 (0.188)***
mechwasher	0.172 (0.103)*	0.453 (0.161)***
vehicle	-0.021 (0.105)	0.707 (0.158)***
premises	0.514 (0.104)***	0.609 (0.229)***
window	0.288 (0.103)***	0.329 (0.300)
machinery	0.102 (0.111)	0.858 (0.178)***
dust	0.097 (0.105)	-0.711 (0.181)***
closed	-0.261 (0.109)**	0.824 (0.162)***
Duration	-0.027 (0.070)	
No. observations (=N*8*2)	4,800	
LL	-1581.262	
Pseudo R^2	0.052	

*Estimated model = mixed logit, assuming normal distributions for all variables except for duration which was fixed. Dependent variable for model = choice, a {0,1} dummy variable indicating that the option was chosen. Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%. Variables are as defined in Table 17. The "LL" value shows the log likelihood of the model at convergence.*

7.4 Willingness to Pay Findings

Table 24 and Table 25 show the above econometric results converted into units of TUB/NEUB duration for households and non-households respectively. As described above, the results shown are the number of months that would need to be taken off a TUB/NEUB, all else equal, to compensate customers for having the type of water use in question being prohibited rather than permitted.

For households, water uses preferred to be allowed include:

- Watering a garden using a hosepipe
- Watering plants using a hosepipe
- Cleaning a private vehicle using a hosepipe
- Cleaning household walls or windows using a hosepipe
- Cleaning paths, patios or outdoor surfaces using a hosepipe

These results include typical activities for the ordinary household. In contrast, activities relevant only a minority of households such as cleaning boats, filling a swimming pool or maintaining a fountain or a pond, for instance, are all found to have negative values, implying that customers would prefer to have them banned during a TUB, all else equal.

A similar pattern is observed for non-households in Table 25. Activities expected to affect a large number of enterprises across different sizes and industries such as "Cleaning premises", "Cleaning windows of a budilding" or "Watering outdoor plants" are highly positive. For instance, respodnents would prefer a 19 months extension of a NEUB over a restricton on cleaning non-domestic premises. Conversely, water uses that seem typical to specific industries or, however, are less vital for the uphold of the day-to-tay business are rather given up in return for a shorter NEUB. The findings are graphically presented in Figure 7 and Figure 8.

Generally, the values at both end of the scale seem to be higher and lower that the results found for the PR14; this applies especially to the non-household sample. A direct cmparison, however, is not possible as this study has investigated more uses and their values are only applicable in comparison to each other, as described earlier,

Table 25: SP2 WTP results - households

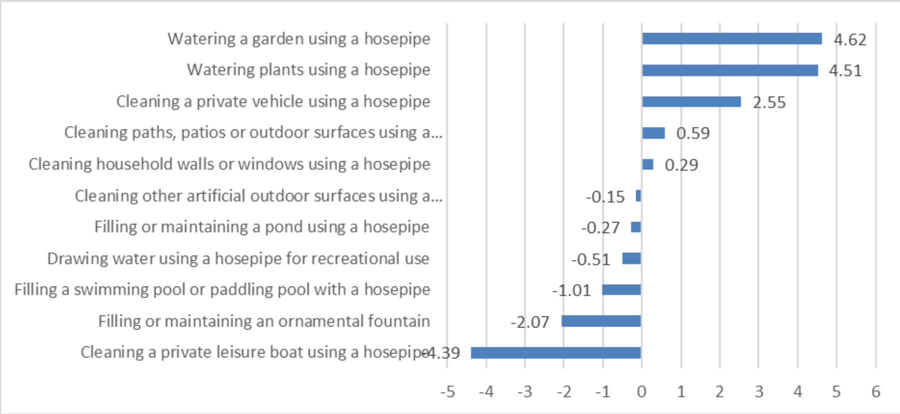
Variable	**Households [Months]**
Watering a garden using a hosepipe	4.62
Watering plants using a hosepipe	4.51
Cleaning a private vehicle using a hosepipe	2.55
Cleaning paths, patios or outdoor surfaces using a hosepipe	0.59
Cleaning household walls or windows using a hosepipe	0.29
Cleaning other artificial outdoor surfaces using a hosepipe	-0.15
Filling or maintaining a pond using a hosepipe	-0.27
Drawing water using a hosepipe for recreational use	-0.51
Filling a swimming pool or paddling pool with a hosepipe	-1.01
Filling or maintaining an ornamental fountain	-2.07
Cleaning a private leisure boat using a hosepipe	-4.39

Results show the number of months that would need to be taken off a TUB to compensate respondents for having the type of water use in question prohibited rather than permitted during a TUB

Table 26: SP2 WTP results – non-households

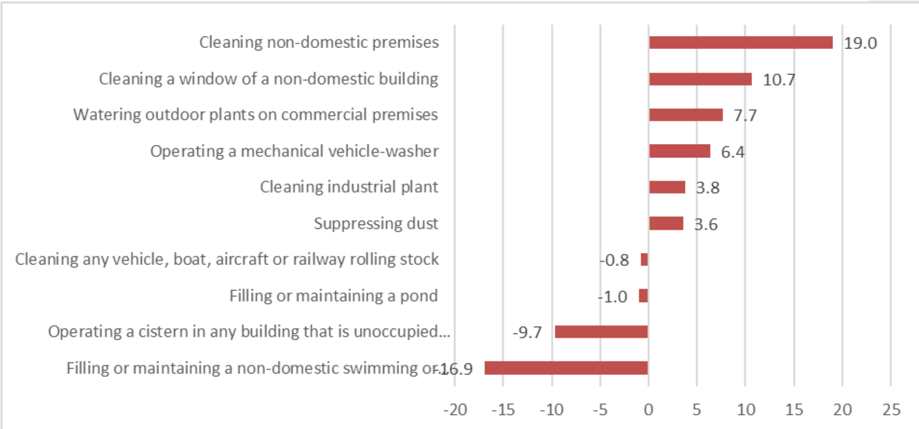
Variable	**Non-Households [Months]**
Clean non-domestic premises	19.05
Cleaning a window of a non-domestic building	10.67
Watering outdoor plants on commercial premises	7.68
Operating a mechanical vehicle-washer	6.37
Cleaning industrial plant	3.79
Suppressing dust	3.61
Cleaning any vehicle, boat, aircraft or railway rolling stock	-0.78
Filling or maintaining a pond	-0.97
Operating a cistern in any building that is unoccupied and closed	-9.68
Filling or maintaining a non-domestic swimming pool	-16.94

Figure 6: WTP for water use types to be allowed during temporary use ban, in terms of increased duration of the ban - households



Source of WTP estimates: Table 24. Positive values indicate that customers would be willing to face a longer duration of temporary use ban for the water use type to be allowed. Negative values indicate that customers would be willing to face a longer duration of temporary use ban for the water use type to be prohibited.

Figure 7: WTP for water use types to be allowed during temporary use ban, in terms of increased duration of the ban – non-households



Source of WTP estimates: Table 25. Positive values indicate that customers would be willing to face a longer duration of temporary use ban for the water use type to be allowed. Negative values indicate that customers would be willing to face a longer duration of temporary use ban for the water use type to be prohibited.

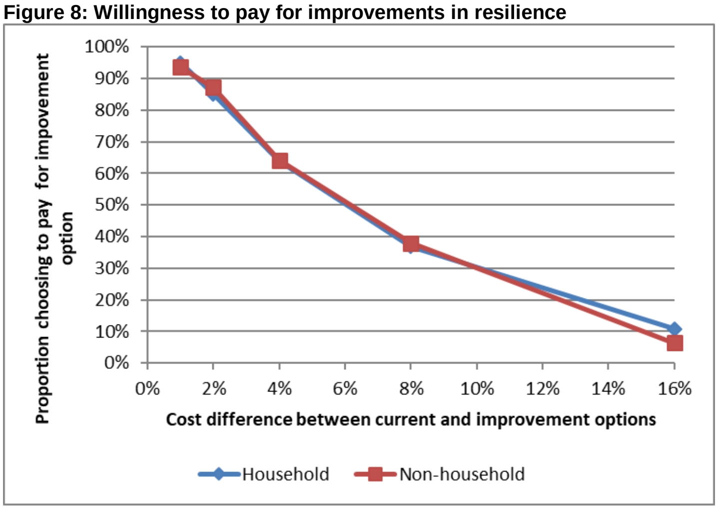
8. SP3 FINDINGS - RESILIENCE VALUATION

The SP3 exercise differed from the two previous exercises as the focus was shifted from TUBs/NEUBs to the prospect of a rota cuts. The exercise asked respondents questions to elicit their WTP for an improvement from 1 in 100 to 1 in 200 in the annual risk of rota cuts.

Figure 9 shows the proportion or respondents choosing the improvement option (1 in 200 frequency of rota cuts), rather than the current service option (1 in 100) when asked directly via the CV questions. The proportions are calculated such that if a respondent said "yes" to, say "16%", they are also included in the proportion shown as being willing to pay all amounts less than 16%. Likewise, if a respondent said "no" to, say "2%", they are also included in the proportion shown as being unwilling to pay all amounts greater than 2%.

The costs shown represent the permanent real increase in the customer's bill for the improved level of service, rather than a one-off payment.

Figure 8: Willingness to pay for improvements in resilience



Base: Households =400; Non-households =300. (1) Figures show the proportions choosing the improvement option (1 in 200) rather than the current service option (1 in 100) at each cost difference between current and improvement options shown in the contingent valuation questions, expressed as a percentage of the respondent's current water and sewerage bill amount. (2) Proportions are calculated as the number choosing the improvement option at the cost difference shown, or any amount higher than this, divided by this plus the number choosing the current option at the cost difference shown or any amount lower.

The chart in Figure 9 shows that many DCWW customers attached a high value to the improvement in resilience from 1 in 100 to 1 in 200, and that there was a high degree of consistency in the answers of households and non-households to these questions.

An estimate of mean WTP can be obtained from these figures via the 'Turnbull' method. This method calculates a lower bound on WTP by assuming that the proportion willing to pay a given amount is the proportion of the sample that accepted that amount if/when it was offered to them in the scenario.

The advantage of the Turnbull analysis is that it does not impose any restrictions on the distribution of preferences in the sample. However, it is weak, in comparison with parametric regression methods, in identifying the effects of multiple explanatory variables on WTP. Moreover, the resulting value potentially under-states true WTP due to the fact that it is explicitly a lower-bound rather than a central estimate of mean WTP.

Using this method, we calculate an estimate of lower bound mean WTP for the improvement from 1/100 to 1/200 in the annual risk of rota cuts of 5.4% of households' current bills, on average, in real terms, and 5.1% of non-households' current bills. This equates to £23.70 per household per year and £96.80 per year, on average, for non-households.

9. SP4 FINDINGS – METERING OPTIONS

The SP4 exercise asked customers to choose which of the three options described in section 2 they would most like to see, and which they would least like to see. In summary, the options were as follows:

- Option 1 – Compulsory metering policy
- Option 2 – Progressive metering policy
- Option 3 – Optional metering policy

Our main findings from these choices are based on Most-Least preference scores. These are calculated as the proportion of times each option was marked as 'most like to see' minus the proportion of times the option was marked as 'least like to see'. (See Marley and Louviere, 2005, for a proof that this simple metric is a sufficient statistic for a full multinomial logit model.)

Table 26 presents our main findings. For households, each option captured an approximately equal share of customers choosing it as their most preferred alternative. However, the Progressive metering policy was marked as the least preferred option by the smallest number of customers and, as such, Option 2 obtains the highest Most-Least score for households.

For non-households, Option 2 was chosen as the most preferred alternative most often, and chosen as the least preferred alternative least often. Option 2 therefore also obtains the highest Most-Least score for non-households.

Table 27:SP4 main findings

	Most preferred (%)	Least preferred (%)	Most-Least (%)
Households			
Option 1 (Compulsory)	31.7	54.3	**-22.7**
Option 2 (Progressive)	34.1	7.1	**27.0**
Option 3 (Optional)	35.9	37.7	**-1.8**
Non-households			
Option 1 (Compulsory)	37.7	31.6	**6.1**
Option 2 (Progressive)	49.0	6.3	**42.7**
Option 3 (Optional)	18.5	59.6	**-41.1**

In contrast to the consistent preference for Option 2 amongst households and non-households, the next highest scoring option for households was Optional metering (Option 3) whereas non-households' next preferred option was Compulsory metering (Option 1). Indeed, compulsory metering commanded a positive Most-least score for non-households but a negative score for households, a result that is consistent with the SP1 findings reported above.

10. CONCLUSIONS AND RECOMMENDATIONS

The research presented in this report has examined customers' preferences in relation to the many ways that DCWW could manage its water resources in future, and in relation to the types of water use restrictions that it could impose during a temporary use ban. A robust stated preference approach was used in each case.

By way of conclusion, this section summarises the main findings for each part of the research, and provides an assessment of the validity of the results.

10.1 SP1 - Water Resources Management

The water resources management options component of the research obtained monetary estimates of customers' willingness to pay for certain measures, and willingness to accept other measures in exchange for lower bills. These results were obtained as 'external' values, net of the value of the impact of each measure on the water supply-demand balance itself.

Results are largely consistent with expectations showing that a reduction in the leakage rate from 22% to 20% has the biggest value to households followed by the re-opening of existing unused reservoirs, new waste water works and a further bigger reduction from 20% down to 15%. Consisted across households and non-households is the negative WTP for new river or groundwater abstractions. The biggest difference between both groups is observed for compulsory metering; while they come out as one of the most valued measures for non-households, households would prefer them not to be undertaken, all else equal.

The estimates obtained from this research can be used in cost-benefit appraisals of alternative supply-demand measures for inclusion in DCWW's water resources management plan. Each value could be treated as an additional benefit, over and above the value associated with the supply-demand impact of the measure in question, which would offset some of the financial cost associated with implementing the measure. Inclusion of these values in cost-benefit appraisals could affect the set of options being chosen as optimal from the point of view of customers for DCWW's water resources management plan.

10.2 SP2 - Water Use Restrictions

The water use restrictions component of the research obtained estimates of customers' willingness to pay, in terms of increased TUB/NEUB for having certain uses allowed rather than prohibited.

Results revealed a clear pattern applicable to both customer groups with water uses relevant to a large majority of the respective property exhibiting a high WTP in the sense that respondents are willing to accept a significant extension of the duration of the hose ban to avoid restriction. Conversely, water uses only relevant to a small minority are preferred to be banned in order to shorten the duration of the TUB/NEUB. The highest valued water use types, by households and non-households are "Watering plants using a hosepipe" and "Clean non-domestic premises", alternatively. The water use most desired to be prohibited are “Cleaning a private leisure boat using a hosepipe” and “Filling or maintaining a non-domestic swimming pool”.

The results obtained from this research can be used in cost benefit-type appraisals of alternative combinations of restrictions for inclusion in DCWW’s drought plan. An economically efficient policy would involve prohibiting all the uses where the values obtained were negative, and further prohibiting uses with positive values where the value of the usage was less than the corresponding number of months duration that would likely be avoided if it were prohibited rather than allowed.

10.3 SP3 - Resilience Valuation

Results from our analysis of the SP3 exercise found that many DCWW customers attached a high value to the improvement in resilience from 1 in 100 to 1 in 200. We calculated a lower bound estimate of mean WTP for the improvement option of 5.4% of households’ current bills, on average, in real terms, and 5.1% of non-households’ current bills. This equates to £23.70 per household per year for households and £96.80 per year, on average, for non-households.

10.4 SP4 - Metering Options

Findings from the SP4 exercise indicated strong support amongst both households and non-households for the Progressive metering policy option (Option 2). However, households next preferred option was Optional metering (Option 3) whereas non-households’ next preferred option was Compulsory metering (Option 1)

10.5 Validity Assessment

Confidence in the results presented in this report can be gained from the following:

- The vast majority of responses were assessed as valid, taking into account respondent and interviewer feedback, and the reasons respondents gave for their choices. (See section 5.)

- Analysis of the sources of variation in WTP showed that results were consistent with expectation in many areas. There was no statistically significant coefficient found that had the opposite sign to expected whereas there were a many statistically significant findings that did have the expected sign.

Overall, the valuation estimates presented appear to be meaningful measures of DCWW customers’ values for the range of supply-demand measures contained within the survey, net of their effects on the water supply-demand balance, and for the range of water use restrictions that could be put in place to manage water resources during a drought. As such, we believe both sets of estimates are appropriate for use in cost benefit analysis for DCWW’s water resources management and drought policy planning.

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APPENDIX A

HH Questionnaire

APPENDIX B

NHH Questionnaire

APPENDIX C

Econometric Analysis of WTP Variation

APPENDIX C ECONOMETRIC ANALYSIS OF WTP VARIATION

C.1 Introduction

An important test of the validity of the WTP results from an SP survey concerns analysing the extent to which WTP varies in line with expectation (Bateman et al. 2002). This appendix reports on the econometric analysis we have conducted to perform this test. Section C.2 focuses on the "water resources management" choice exercise, and section C.3 focuses on the "water use restrictions" choice exercise.

C.2 "Water Resources Management" Choice Exercise (SP1)

The analysis of the SP1 exercise incorporates a number of variables in addition to those included within the main results described in section 6. The following table shows the variables that were used in this analysis, and the mean of the variables in the household and the business samples.

Table 28: Additional variables used in SP1 explanatory choice models

Variable name	Description[(1)]	Mean[(2)]	
		HH	NHH
wantleakage20	"Reduce leakage rate (from 22% to 20%)" cited as top priority	0.263	0.259
wantleakage15	"Reduce leakage rate (from 20% to 15%)" cited as top priority	0.176	0.172
wantmeterord	"Compulsory metering (ordinary meters)" cited as top priority	0.060	0.081
wantmetersmart	"Compulsory metering (smart meters)" cited as top priority	0.064	0.083
wantresexpand	"Expand existing reservoir" cited as top priority	0.091	0.079
wantresreopen	"Re-open existing unused reservoir" cited as top priority	0.248	0.176
wantrecycle	"New wastewater recycling works" cited as top priority	0.111	0.115
wanttransfers_from	"New water transfers from neighbouring companies" cited as top priority	0.032	0.029
wanttransfers_to	"New water to neighbouring companies" cited as top priority	0.028	0.016
wanttransfers_within	"Internal water transfer" cited as top priority	0.021	0.019
wantwsmeasures	"Water saving measures offered to targeted customers" cited as top priority	0.169	0.175
wantabstractnew	"New river or groundwater abstraction" cited as top priority	0.044	0.043
wantabstractreopen	"Re-open existing river or groundwater abstraction" cited as top priority	0.053	0.040
notwantleakage20	"Reduce leakage rate (from 22% to 20%)" cited as not wanted	0.015	0.008
notwantleakage15	"Reduce leakage rate (from 20% to 15%)" cited as not wanted	0.009	0.008
notwantmeterord	"Compulsory metering (ordinary meters)" cited as not wanted	0.118	0.055
notwantmetersmart	"Compulsory metering (smart meters)" cited as not wanted	0.109	0.049
notwantresexpand	"Expand existing reservoir" cited as not wanted	0.065	0.085
notwantresreopen	"Re-open existing unused reservoir" cited as not wanted	0.033	0.034
notwantrecycle	"New wastewater recycling works" cited as not wanted	0.034	0.041
notwanttransfers_from	"New water transfers from neighbouring companies" cited as not wanted	0.110	0.100
notwanttransfers_to	"New water to neighbouring companies" cited as not wanted	0.071	0.058
notwanttransfers_within	"Internal water transfer" cited as not wanted	0.023	0.038
notwantwsmeasures	"Water saving measures offered to targeted customers" cited as not wanted	0.013	0.013
notwantabstractnew	"New river or groundwater abstraction" cited as not wanted	0.100	0.126
notwantabstractreopen	"Re-open existing river or groundwater abstraction" cited as not wanted	0.046	0.034
fartoomuch_bill	Current bill cited as being "Far too much"	0.006	0.006
metr_metord	Household is on a metered tariff	0.128	0.306
metr_metsmart	Household is on a metered tariff	0.114	0.205
use_hose		0.038	0.014

(1) All variables are dummies equal to one if the description is true for the respondent and equal to zero otherwise. (2) "HH" refers to the household dataset; "NHH" refers to the non-household dataset.

The variables in Table 22 entered into the explanatory models as interactions with the original variables from Table 13 in order to test specific sources of variation which carried a theoretical prior. Interaction variables are simply the product of two variables, and are shown in the following models as *Var1* x *Var2*, where *Var1* represents one of the variables from Table 22 and *Var2* represents one of the variables from Table 13.

The first set of interactions included are between indicators from the "naïve priority" questions and the corresponding supply-demand measures. For example, *wantleakage20* is a dummy variable equal to one if the respondent cited 'Reduce leakage to 20%' as one of their top priorities for improvement, and equal to zero otherwise. Likewise, *notleakage20* is a dummy variable equal to one if the respondent cited 'Reduce leakage from 22%to 20%' as one of the measures they would most like not to see implemented, and equal to zero otherwise. These variables were created for all of the supply-demand measures and then interacted with the variables representing the corresponding measures before entering into the model. Accordingly, *wantleakage20* was interacted, ie multiplied by *leakage20*, to obtain the variable *wantleakage20* x *leakage20*. This variable would then be equal to one if the respondent cited 'Reduce leakage from 22%to 20%' as one of their top priorities for improvement and the measure was included within the choice option. It would otherwise take the value zero. Interactions corresponding to each of the "*want*" and "*not*" variables were created and entered into the model likewise.

The purpose of including these interactions was to test that the responses given to the choice exercise were consistent with the responses to the earlier "naive priority" questions in the survey. To be consistent with expectation, the "*want"* interaction variables should take a positive sign for all supply-demand measures and the not interaction variables should take a negative sign for all supply-demand measures. Such a finding would indicate, for example, that respondents choosing a measure as one of their priorities for inclusion in DCWW's plan should give that measure a higher decision weight when making their choices between options than other respondents.

We include an interaction between *bill* and a variable, *fartoomuch*, which indicates that the respondent said their current bill was "Far too expensive". We expect that respondents would be more cost sensitive than other respondents and we would therefore expect that the far*toomuch* x *bill* interaction variable would have a negative coefficient in the explanatory models.

Finally, we include the variable *metered*, which indicates that the household is on a metered tariff, interacted with the supply-demand measures *meterord* and *metersmart*, indicating compulsory metering via ordinary and smart meters respectively. The expectation here was that households on a metered tariff should be relatively less averse to compulsory metering than other households. This is because those households that are currently unmetered would presumably prefer to retain the option over whether to switch to a meter or not, rather than it be made compulsory, whereas this option has no value for households already on a metered tariff. We therefore expect the interaction variables *metered* x *meterord* and *metered* x *metersmart* to each have a positive coefficient.

The explanatory models were estimated using the conditional logit estimator, rather than the mixed logit estimator, due to the fact that a much larger number of parameters were being estimated in the explanatory models than in the main models shown in section 6. The conditional logit models are estimated with robust (Huber-White) standard errors which allow for correlation within individuals' responses.

Table 23 presents two models for households. The first is the full model, including all the variables described above; the second is a restricted specification that includes only interaction variables where they are statistically significant at the 10% level.

The restricted model shows the following findings:

- Five out of the 13 "*want*" interaction variables are statistically significant ($p<.10$) and all of these have the expected positive sign.
- Nine out of the 13 "*not*" interaction variables are statistically significant ($p<.10$), and all of these also have the expected negative sign.
- The two "*metered"* interactions enter the model with the expected positive and statistically significant ($p<.10$) coefficient. This indicates, as expected, that households on a metered tariff were relatively less averse to compulsory metering, (ordinary or smart meters), than other households.
- Overall, the results in Table 23 are supportive of the validity of the results. There are no statistically significant coefficients that have the opposite sign to expected while there are many statistically significant findings that do have the expected sign.