Drought Vulnerability Framework

Final Project Report

Welsh Water

28 March 2019

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Document history

Revision	Purpose description	Originated	Checked	Reviewed	Authorised	Date
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Rev 2.0	Final report	DH LP NU	SA	SA	BC	22/03/2019
Rev 2.1	Final report – addition of further Barmouth analysis	DH LP NU	SA	SA	BC	27/03/2019
Rev 2.2	Final report, following final DCWW review	DH LP NU	SA	SA	BC	28/03/2019

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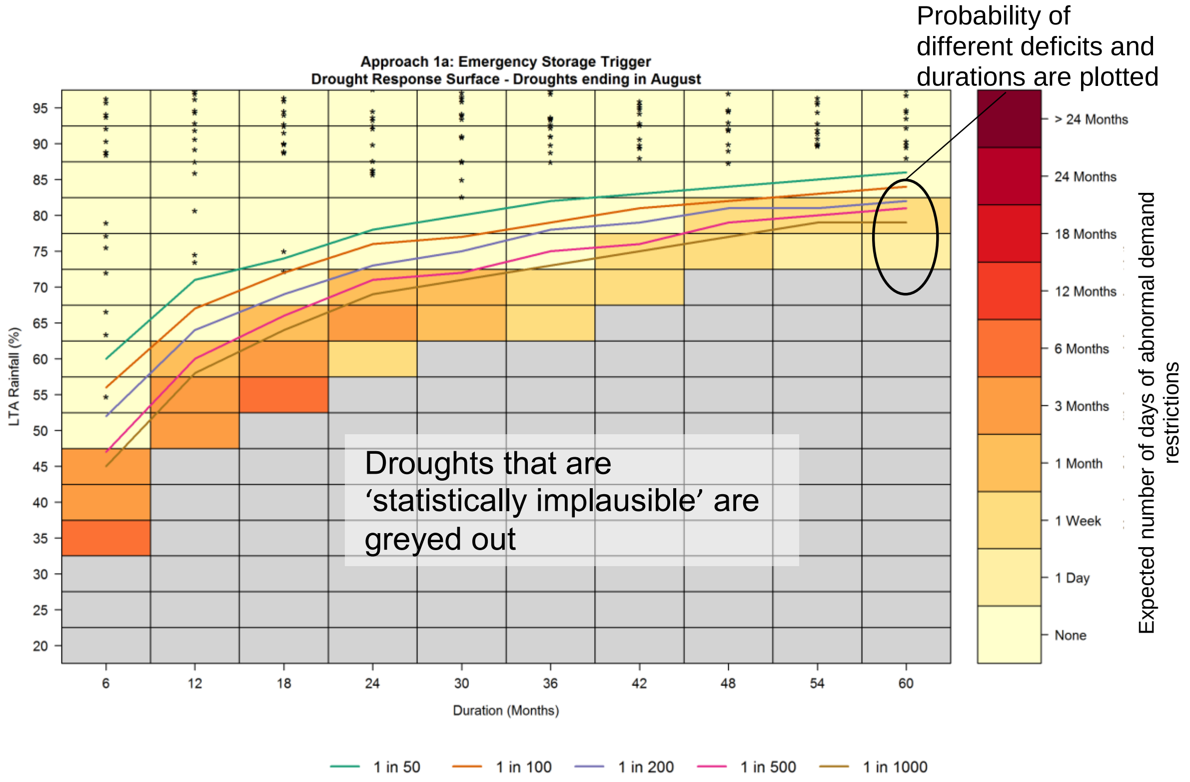
1. Introduction

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 (UKWIR, 2017) 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 0 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.



Probability of different deficits and durations are plotted

Droughts that are ‘statistically implausible’ are greyed out

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 (Atkins 2016) 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 coloured coded in red. WRZs where there was some risk, but it was 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	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

		run through WRAPSim – method 1b	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 (3 months for Tywyn Aberdyfi and Vowchurch). 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				

3.1.2. Drought ending month

As outlined in Section 1, the DRS presents risk over a range of different drought durations. In order to analyse the data for the range of durations tested a fixed drought endpoint must be selected. As a result, each DRS generated corresponds to a specific ending month. This month is selected to coincide with the likely point of highest drought stress, for example at the end of the reservoir drawdown period. The decision is made based on analysis of available date and professional judgement. As some variability is inevitable at least one alternative ending month should be tested.

Typically, September and October have been assessed for the DCWW WRZs. However, in some cases further months have been tested to ensure that that highest level of drought stress has been captured; for example August for Tywyn Aberdyfi (Section 4.4.4) and Vowchurch (Section 4.11.4), and November for SEWCUS (Section 4.12.4).

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.
- The climate change scenario was based on the 50th percentile UKCP09 projections or Future Flows scenario from the WRMP19 climate change assessment (HRW, 2017), i.e. it reflects the central estimate of climate change.

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 (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.

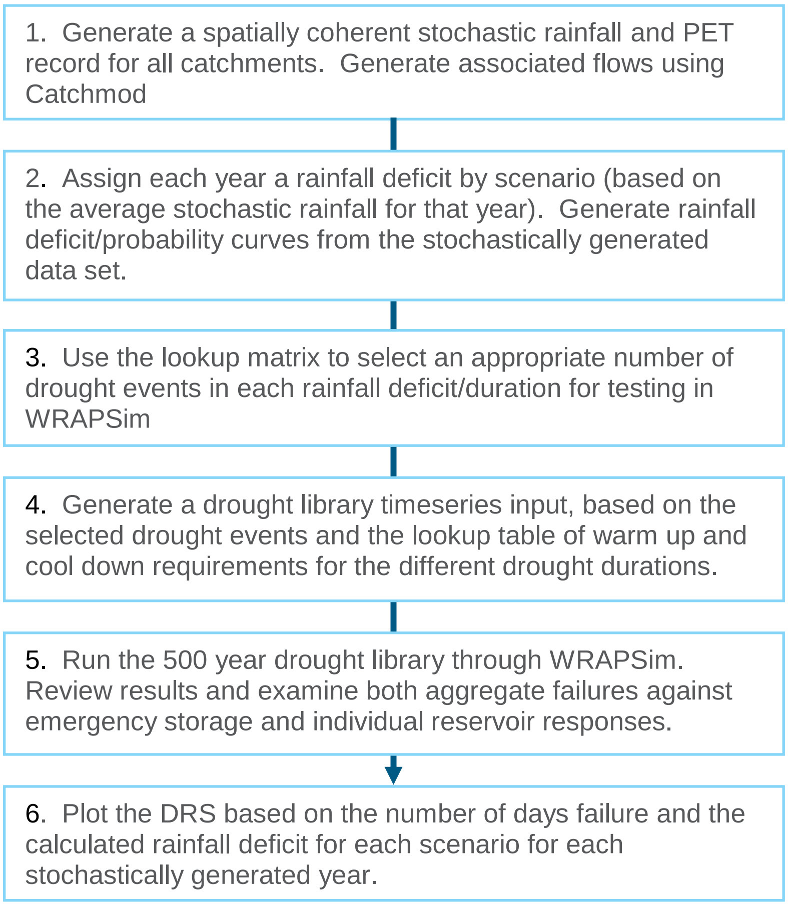
Table 4-1 - Summary of Key Modelling Assumptions

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, Atkins 2019).

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.

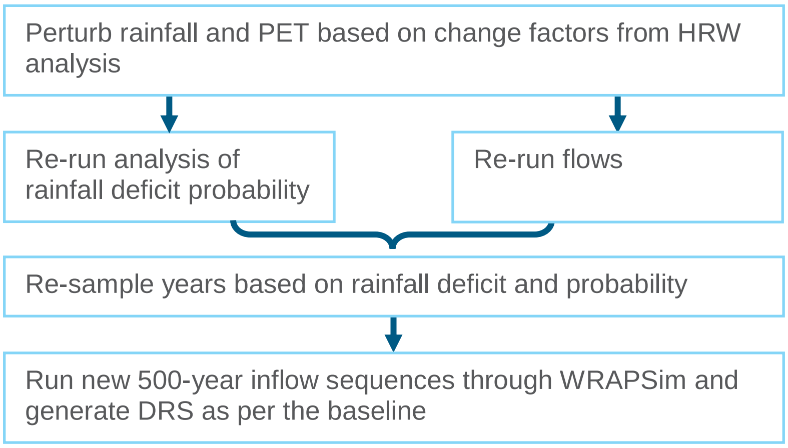


Figure 4-2 - Methodology for the Application of Climate Change

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.

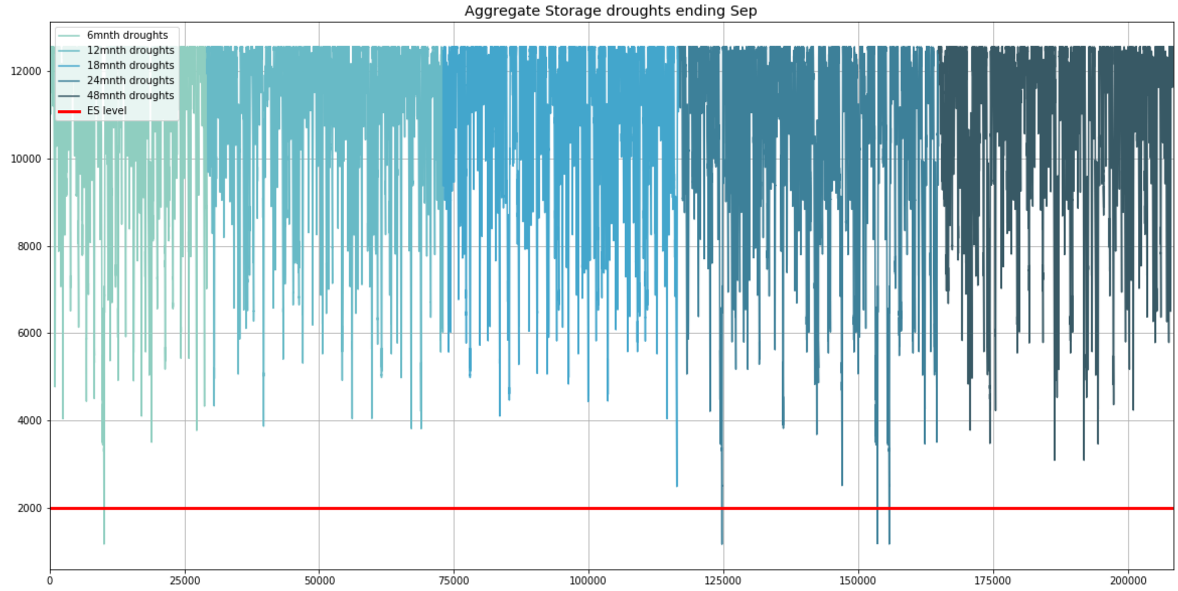


Figure 4-3 - Aggregate Drought Library Results for period ending September

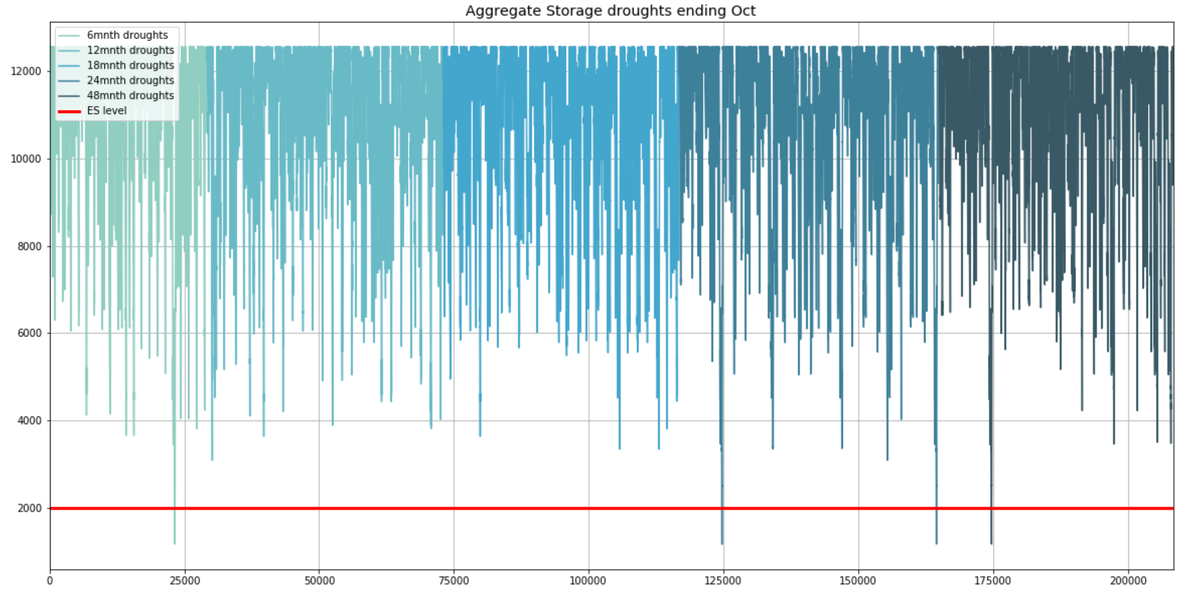


Figure 4-4 - Aggregate Drought Library Results for period ending October

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.

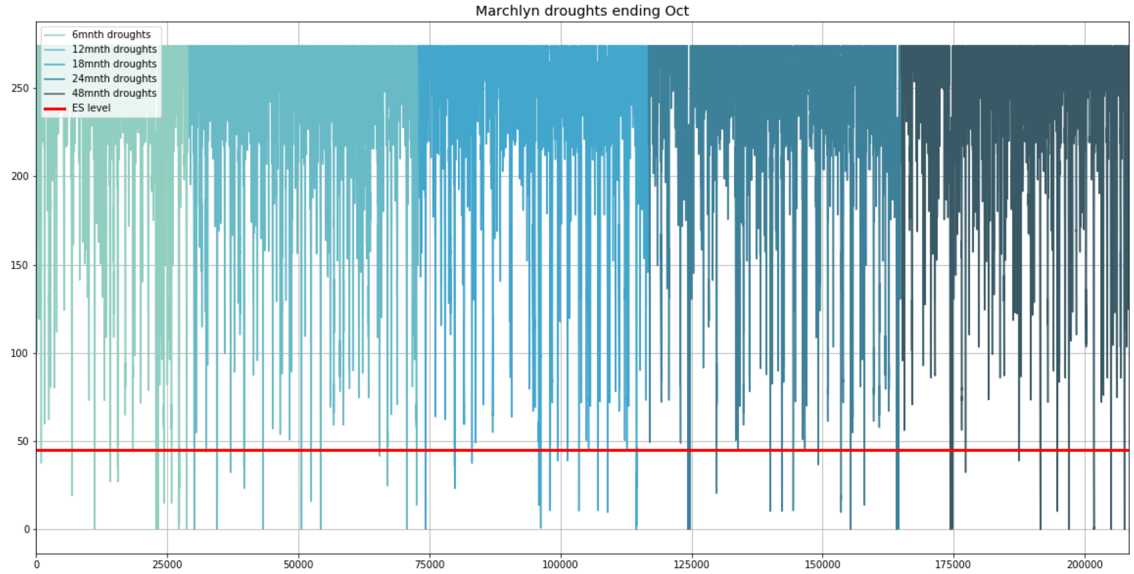


Figure 4-5 - Drought Library Results for Llyn Marchlyn Bach

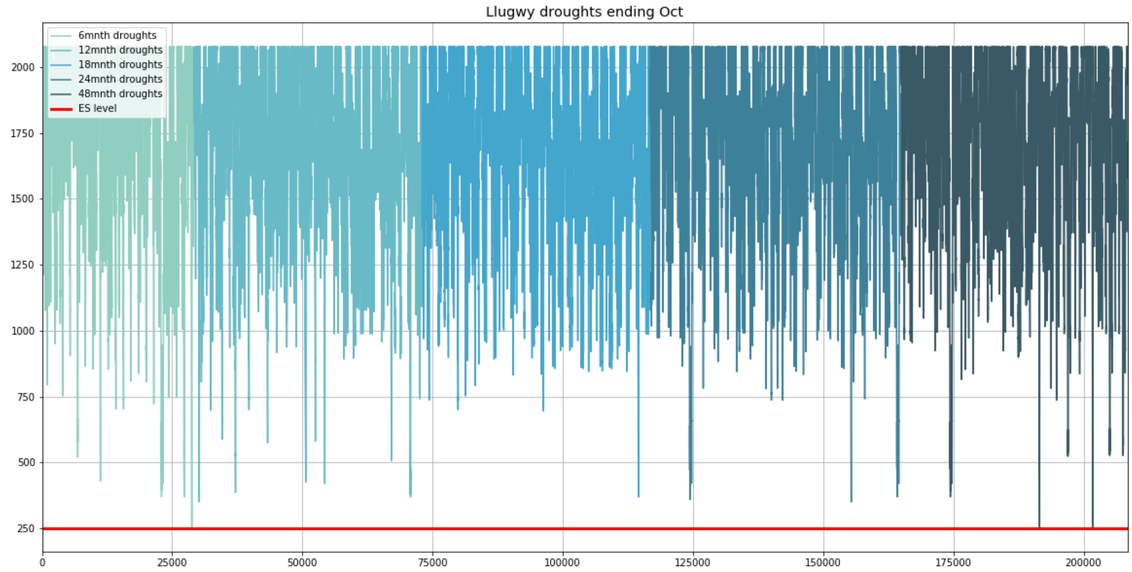


Figure 4-6 - Drought Library Results for Llyn Ffynnon Llugwy

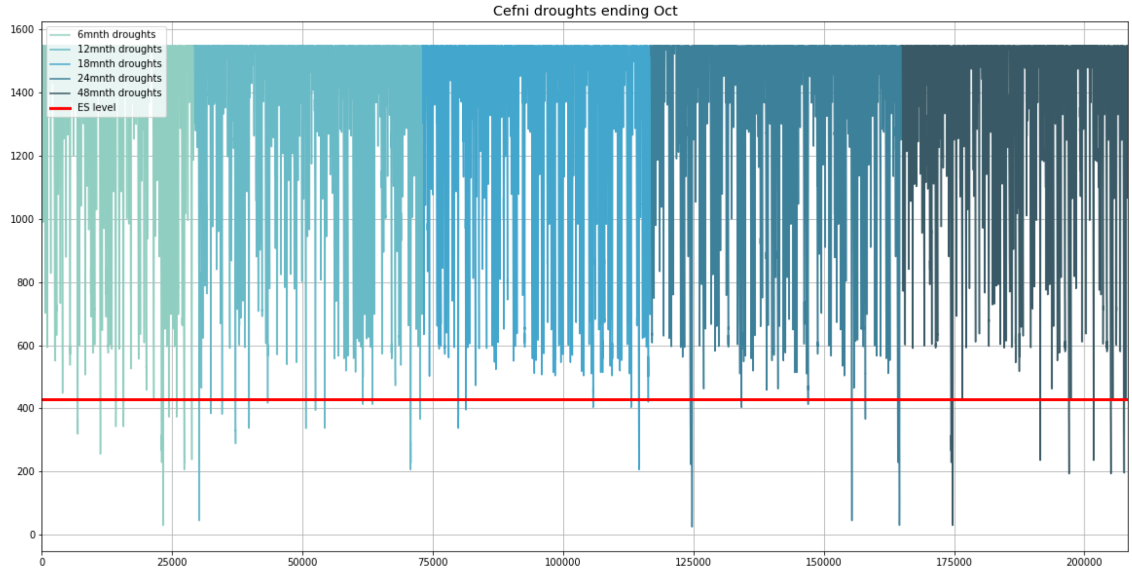


Figure 4-7 - Drought Library Results for Llyn Cefni

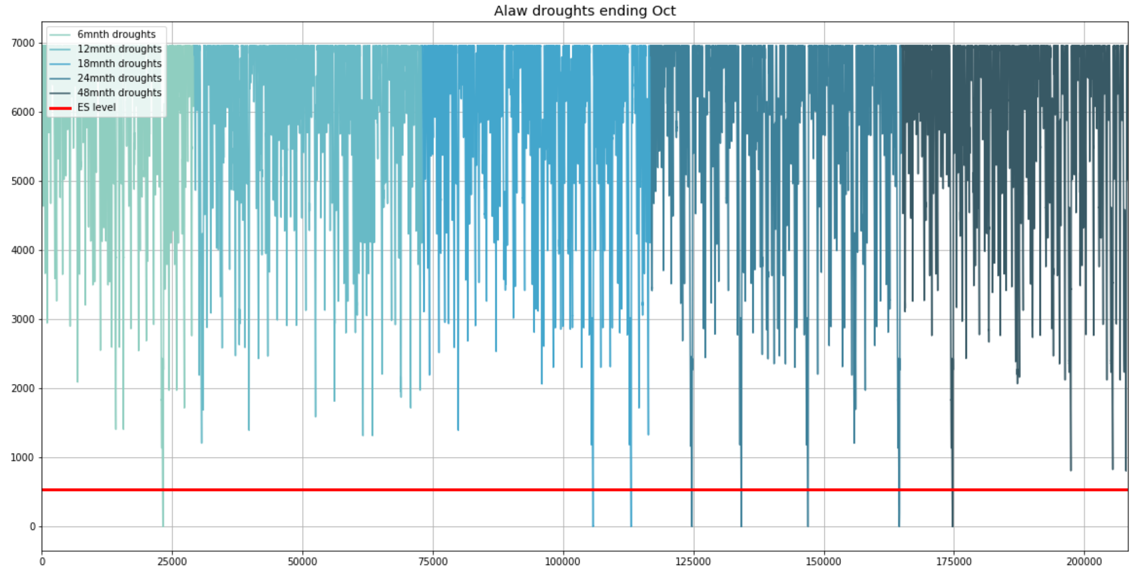


Figure 4-8 - Drought Library Results for Llyn Alaw

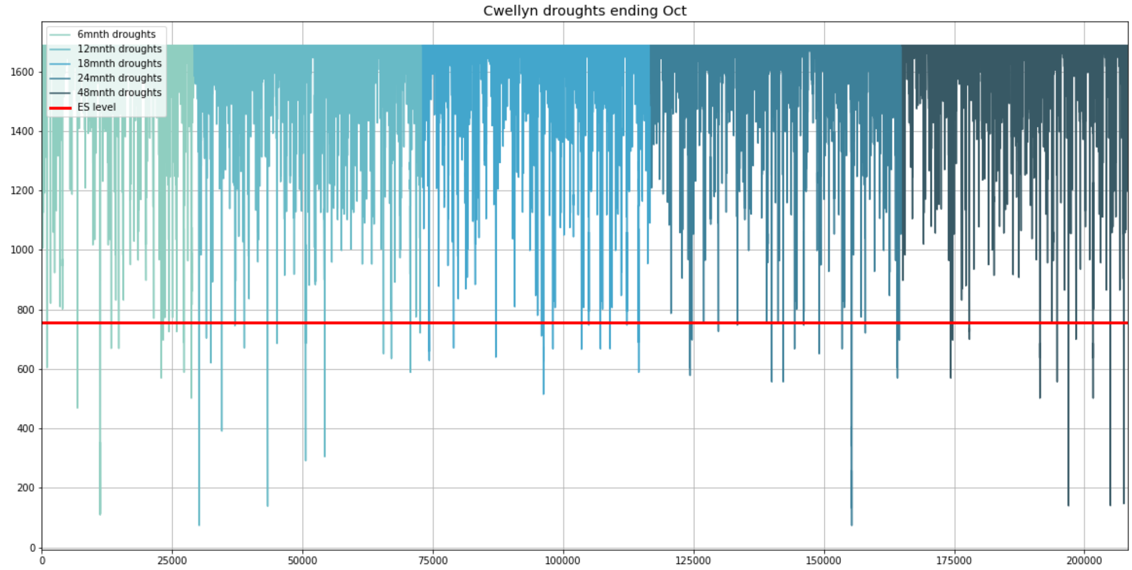
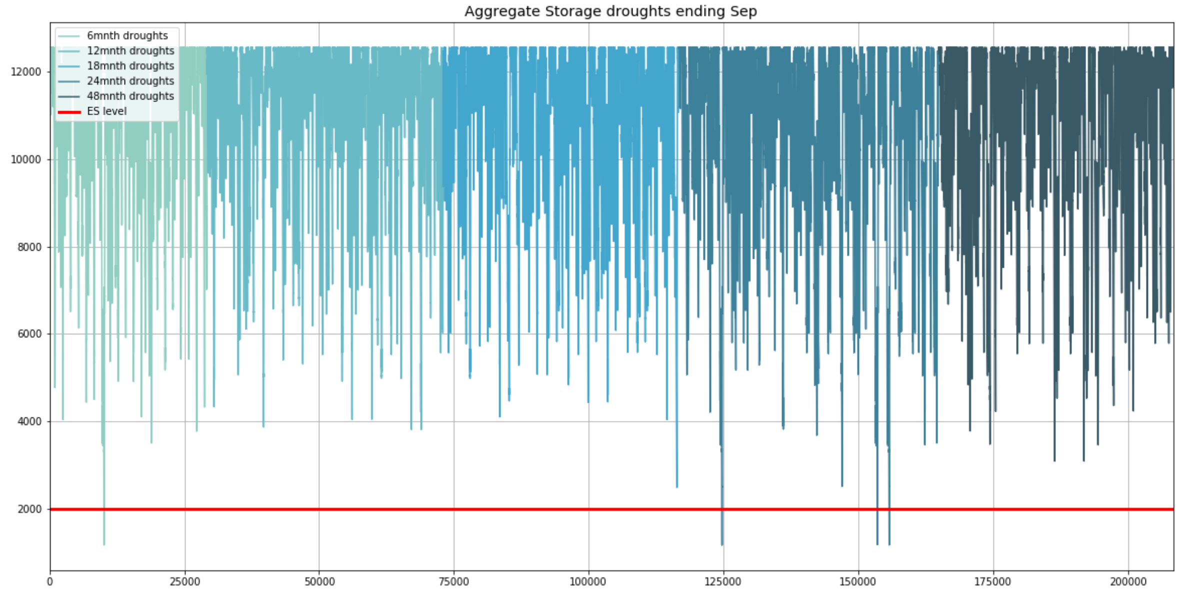


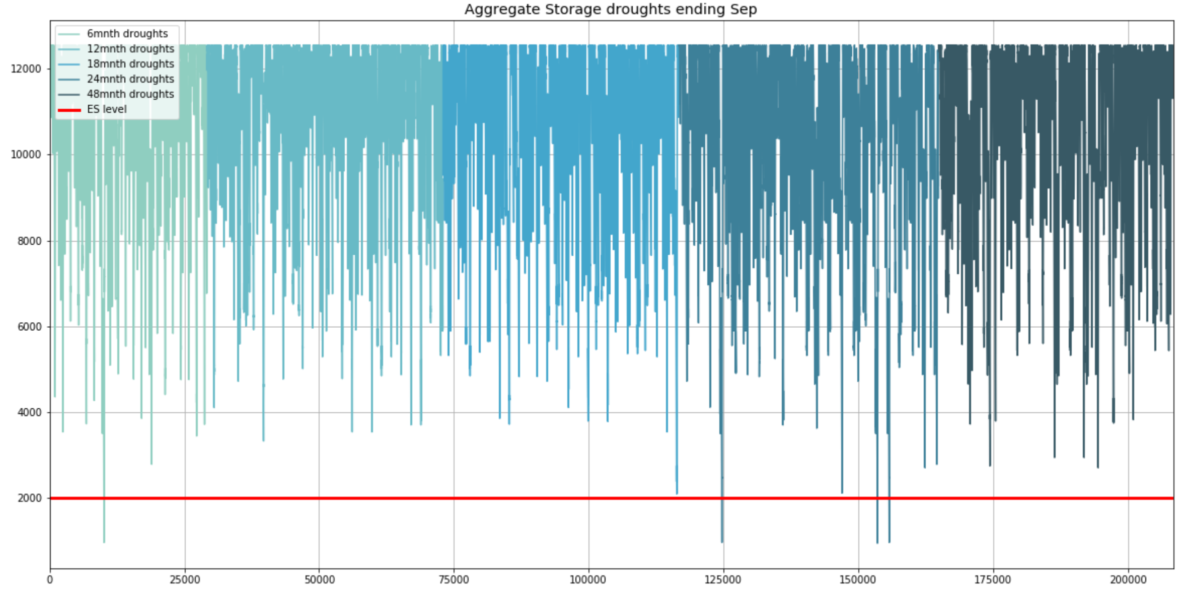
Figure 4-9 - Drought Library Results for Llyn Cwellyn

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.

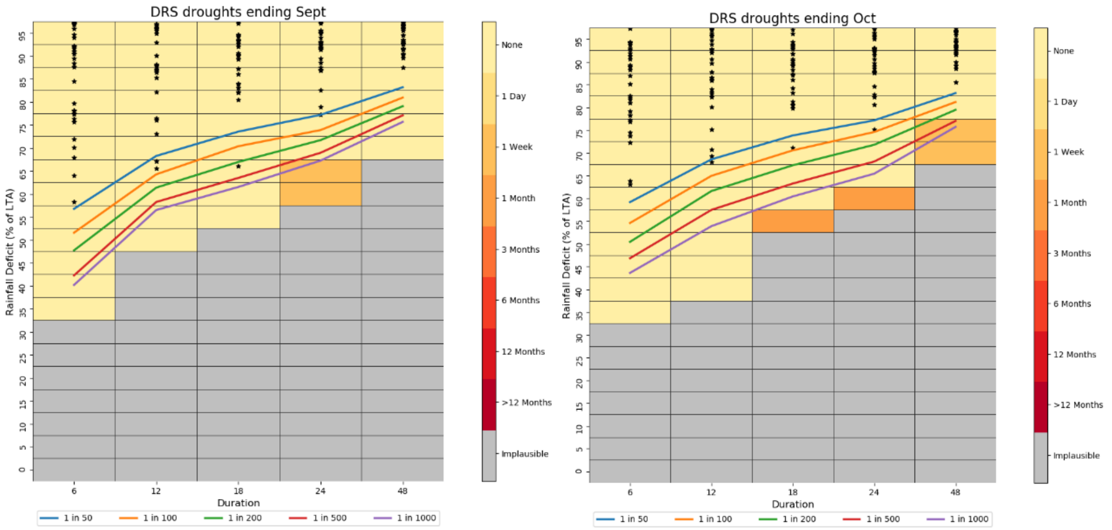


Figure 4-11 Drought Response Surfaces (smoothed) – no climate change

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.

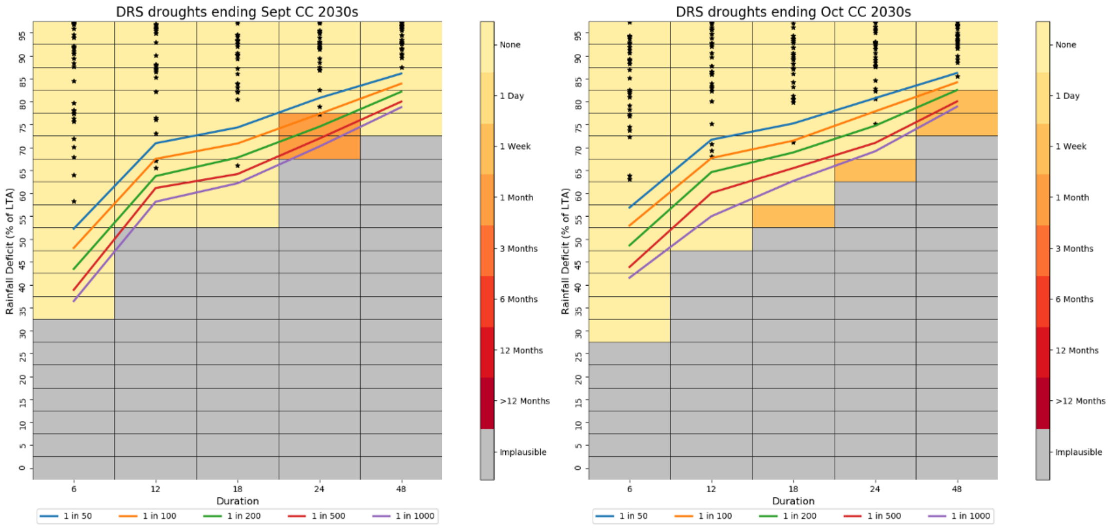


Figure 4-12 - Drought Response Surfaces (smoothed) – with 2030s climate change

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.

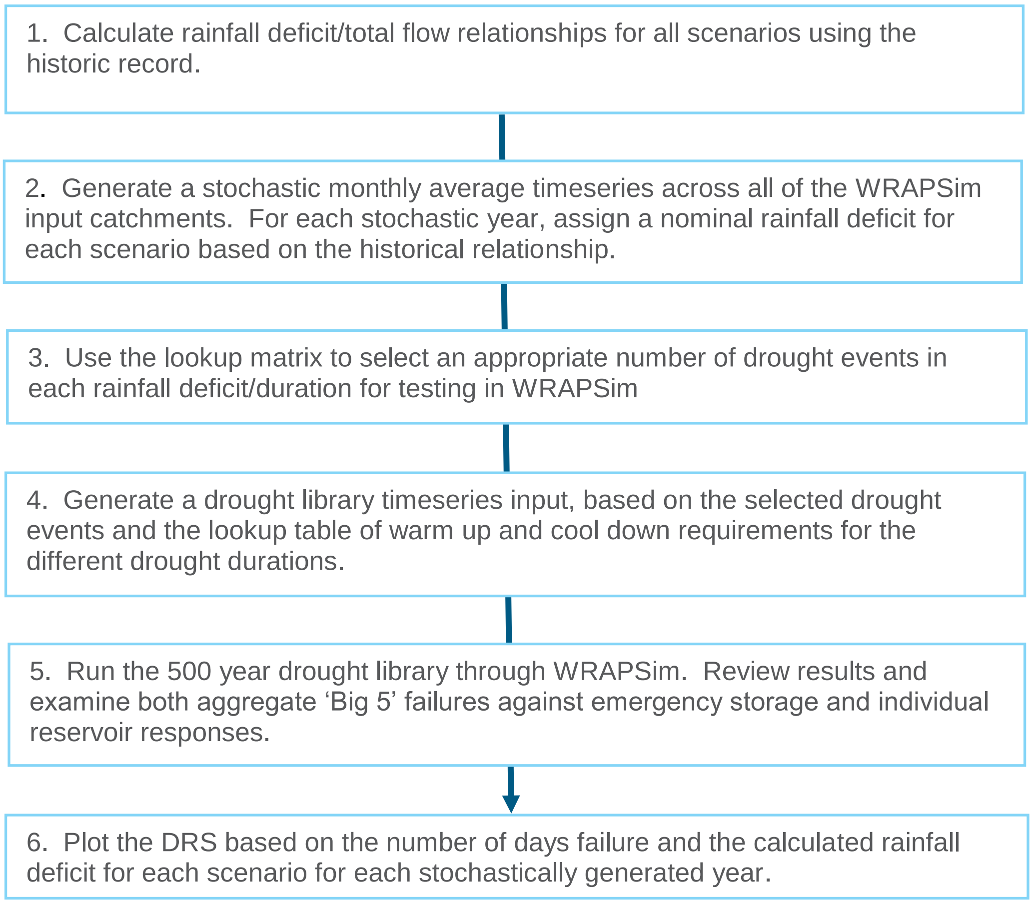
The zonal water resource arrangement is relatively complex and so it was necessary to carry out flow generation as part of the drought vulnerability assessment. However, due to the low risk nature of the WRZ this was completed using one of the simpler DVF assessment methods. Figure 4-2 below presents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

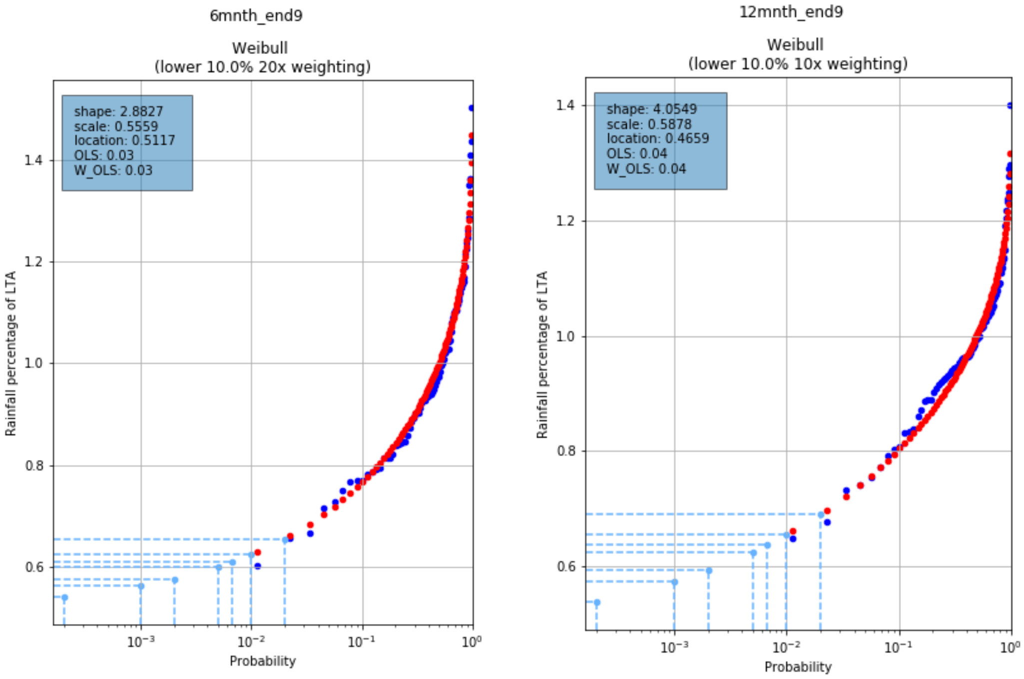
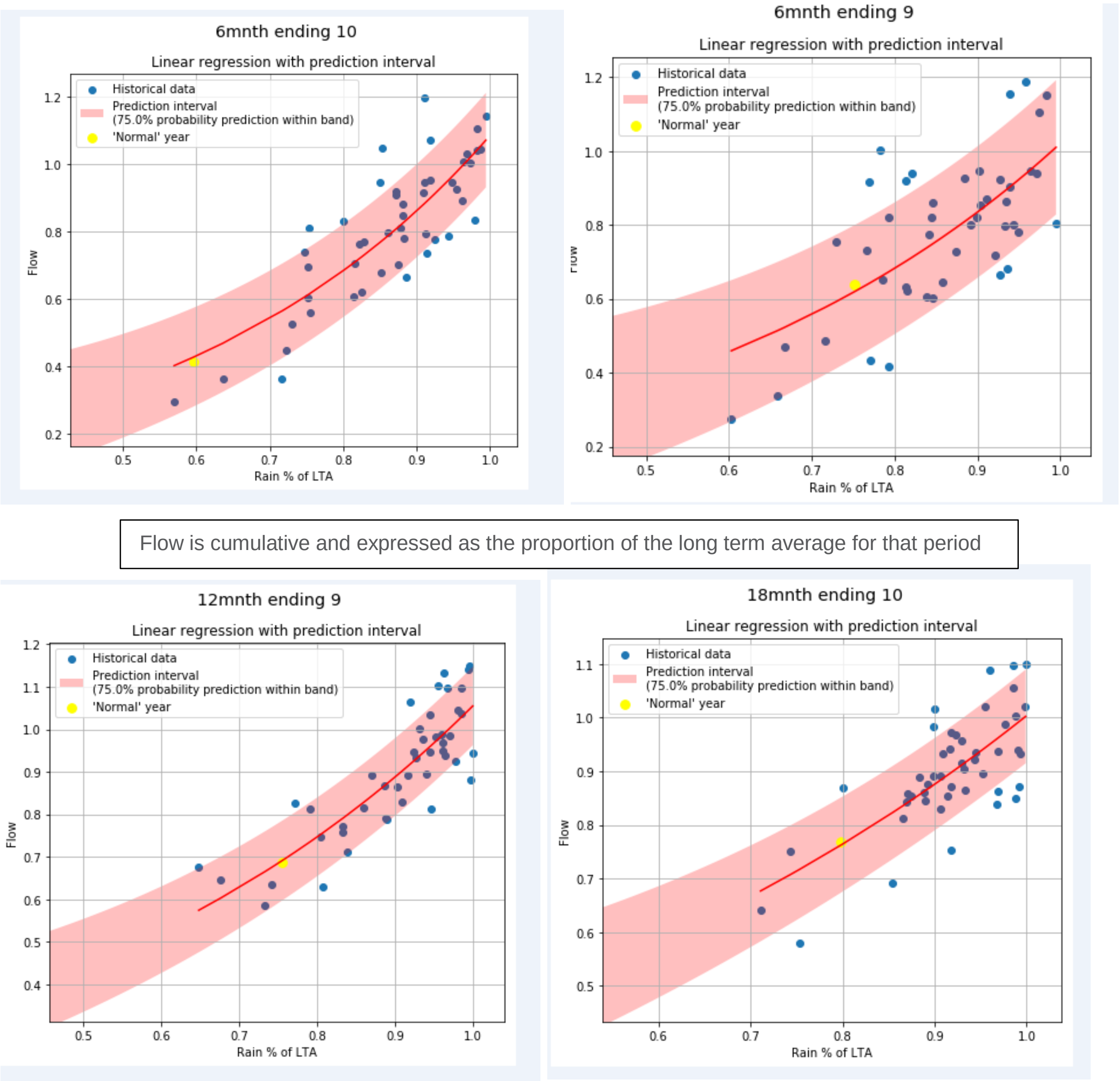


Figure 4-14 - Example EVA Plots for Clwyd Coastal

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).



Flow is cumulative and expressed as the proportion of the long term average for that period

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.

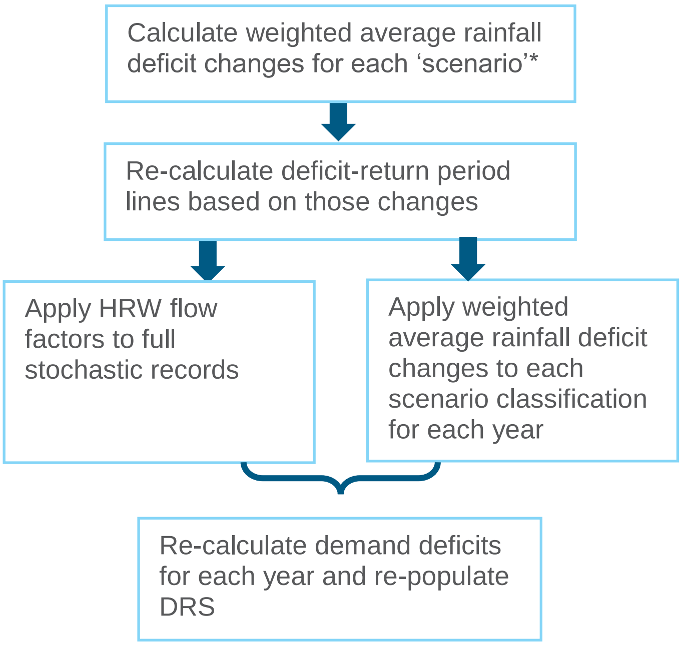
Stage 4: Generation of Flows for the Drought Library

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.

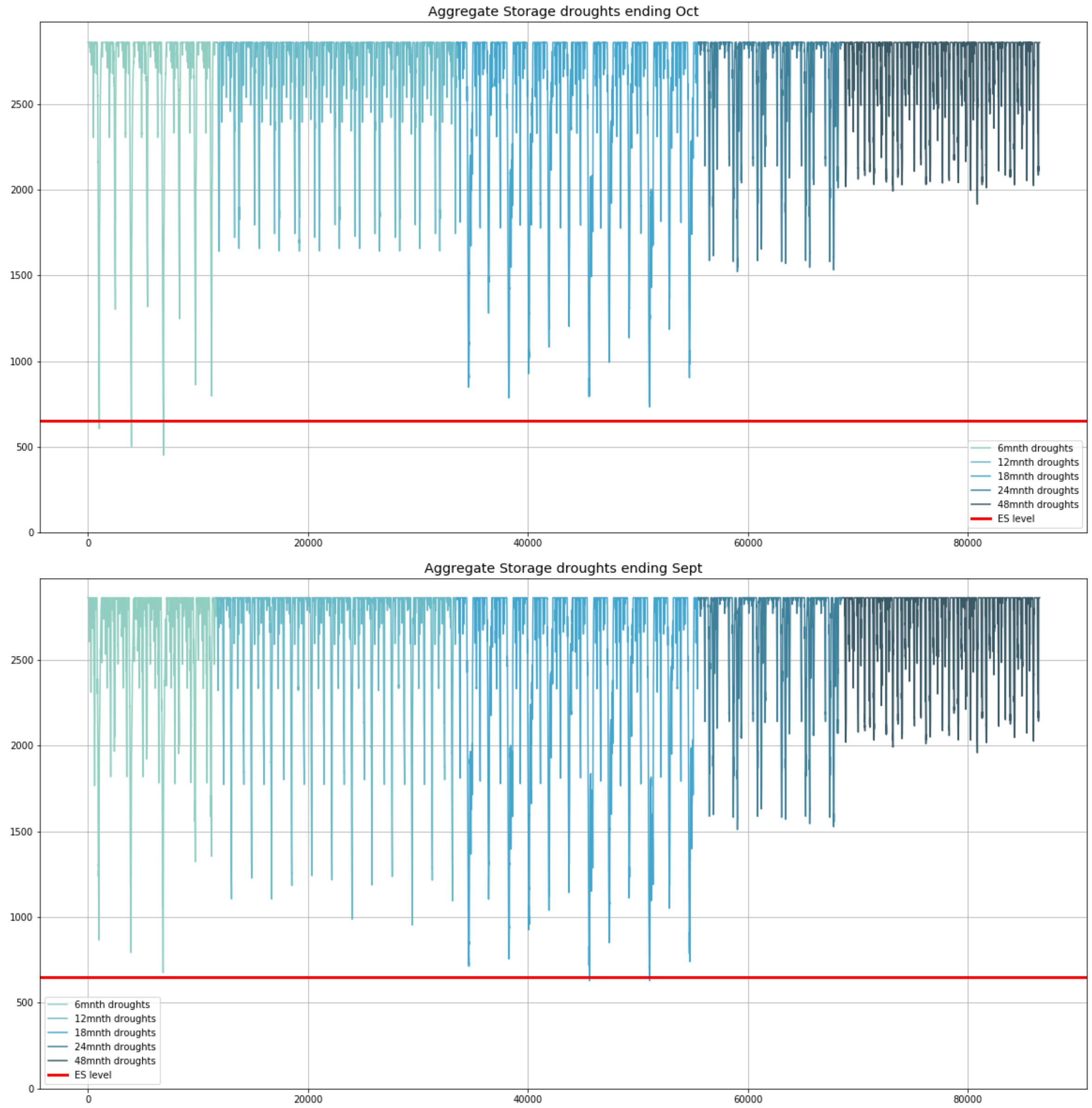


Figure 4-17 - Aggregate Storage Plots for Baseline Drought Events

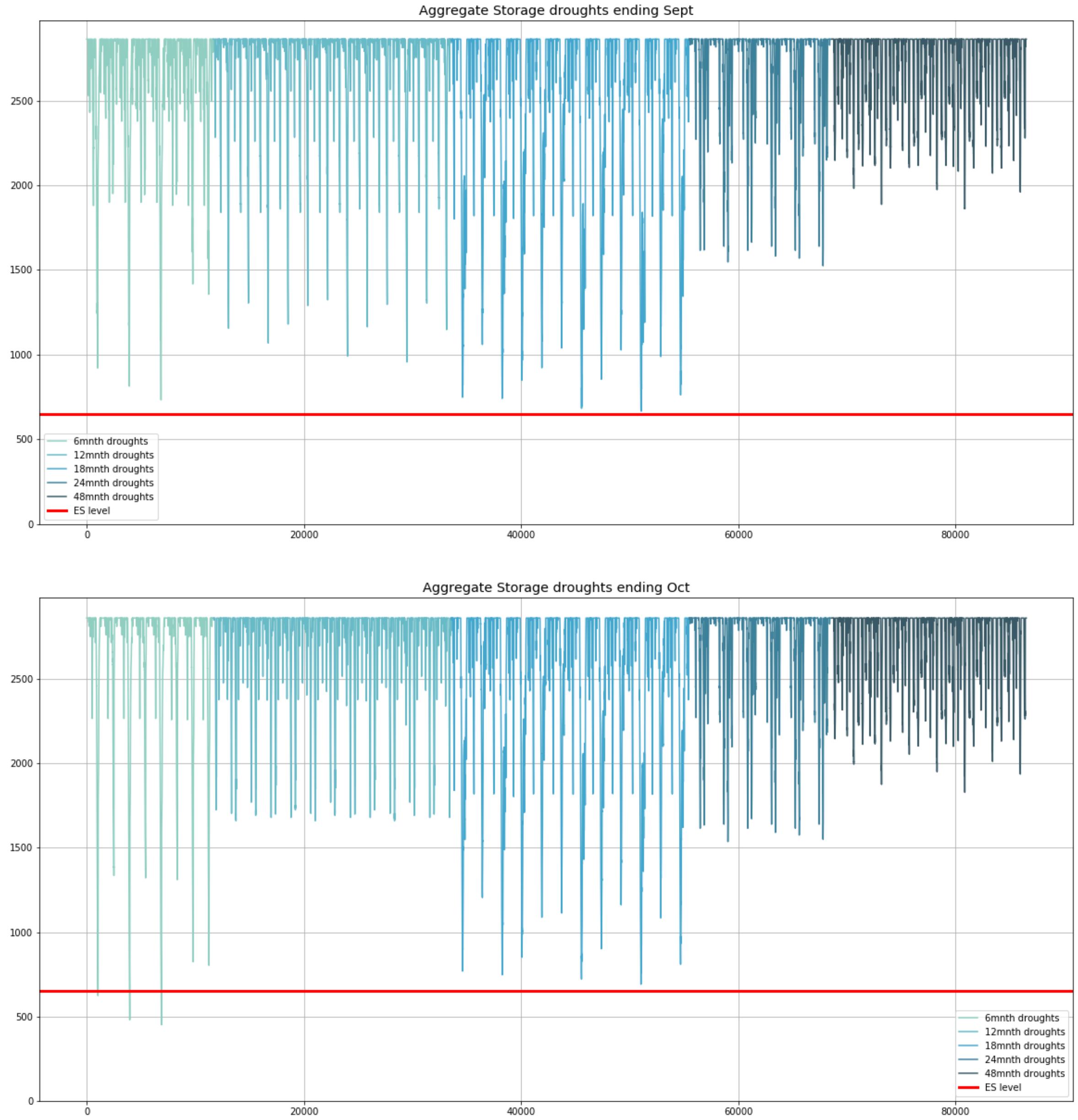


Figure 4-18 - Aggregate Storage Plots for Drought Events with Climate Change

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.

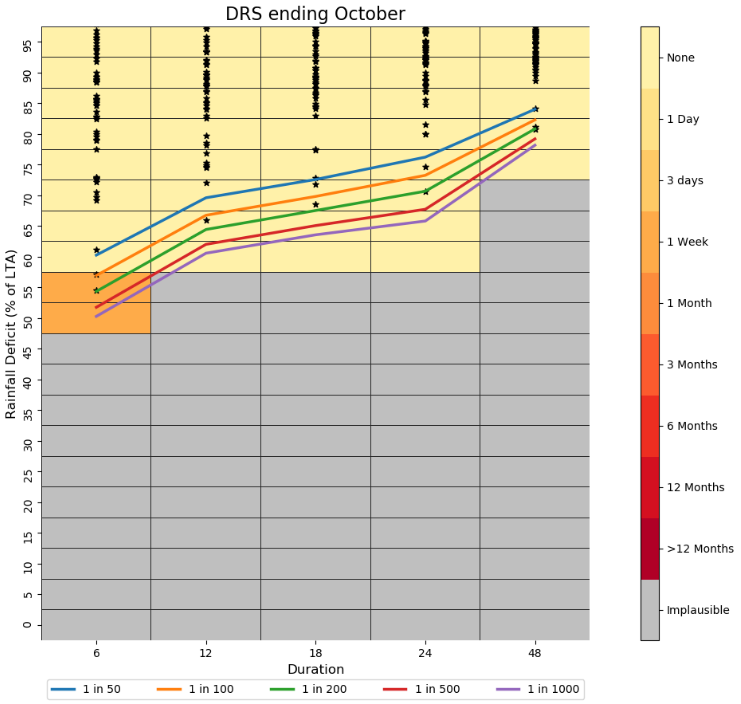


Figure 4-19 - Drought Response Surfaces – no climate change

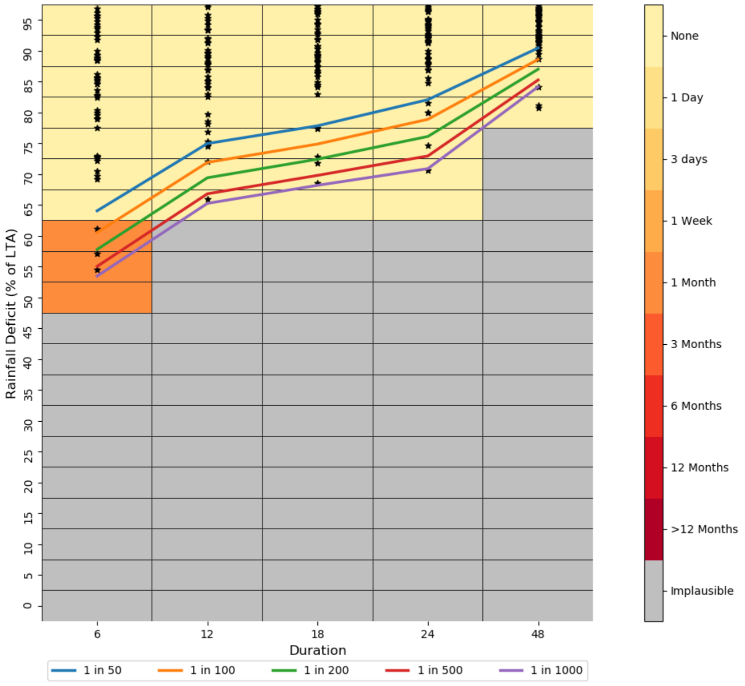


Figure 4-20 - Drought Response Surfaces – with 2030s climate change

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.

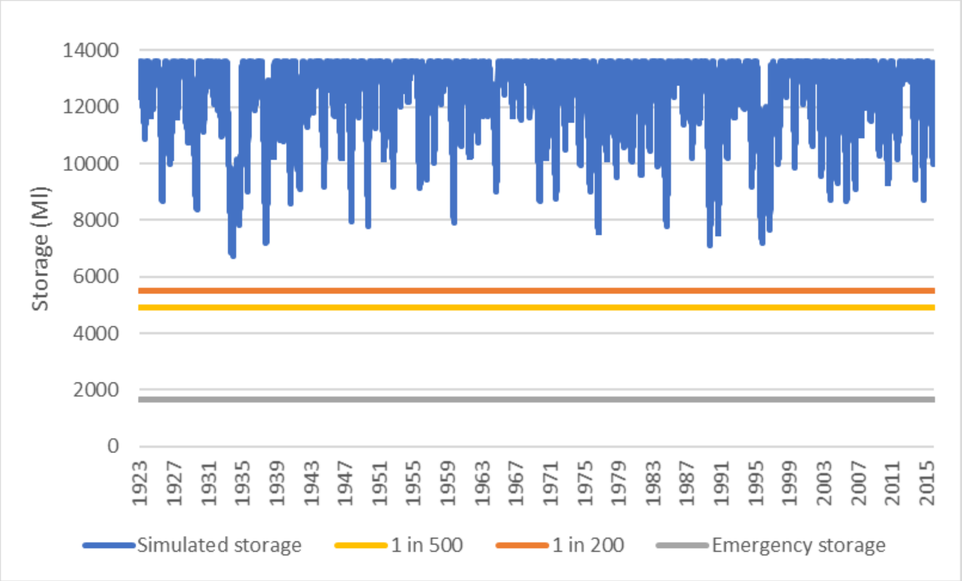


Figure 4-21 - Alwen reservoir extreme value analysis results (baseline)

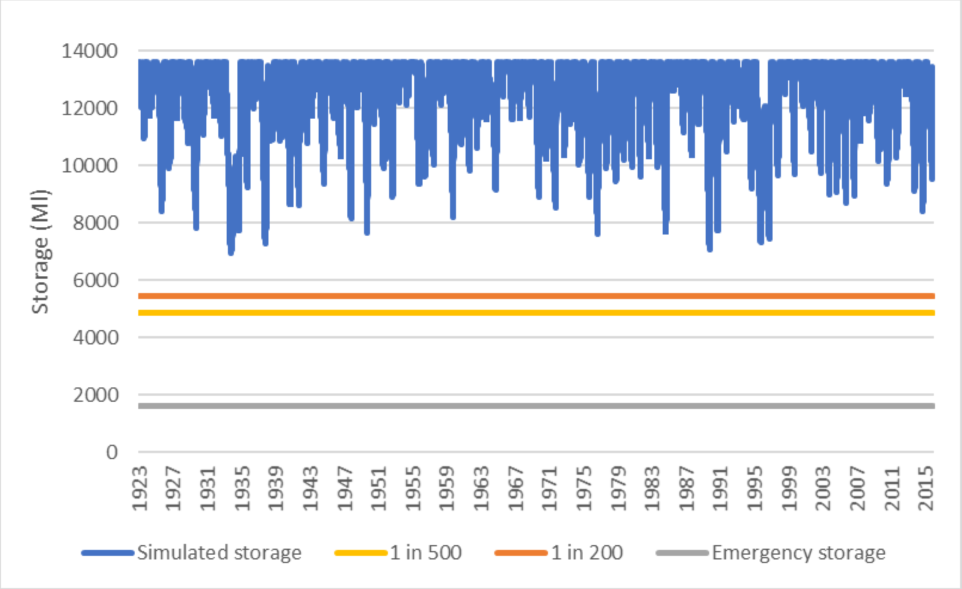


Figure 4-22 - Alwen reservoir extreme value analysis results (2030s)

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.

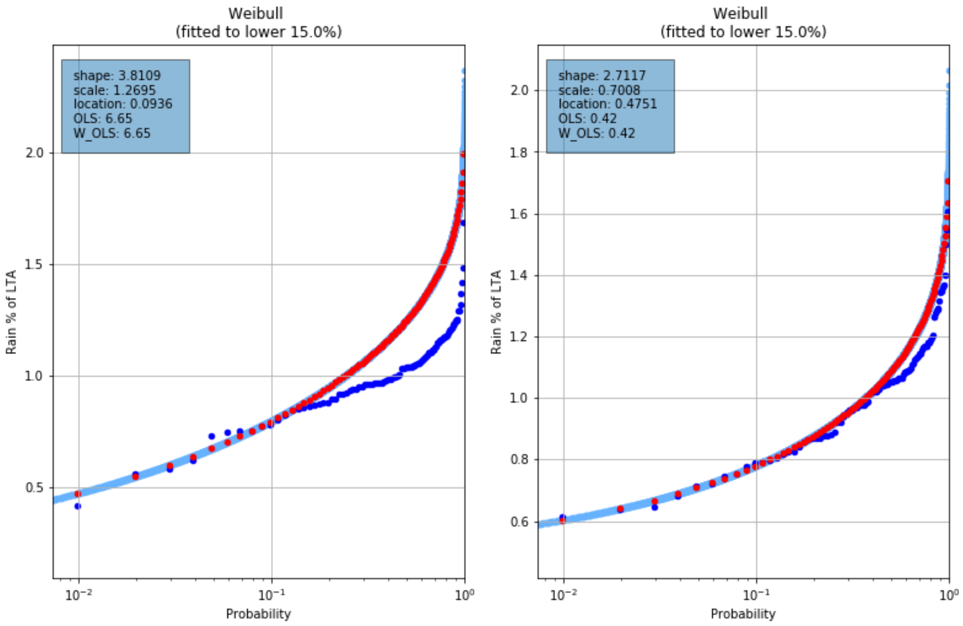
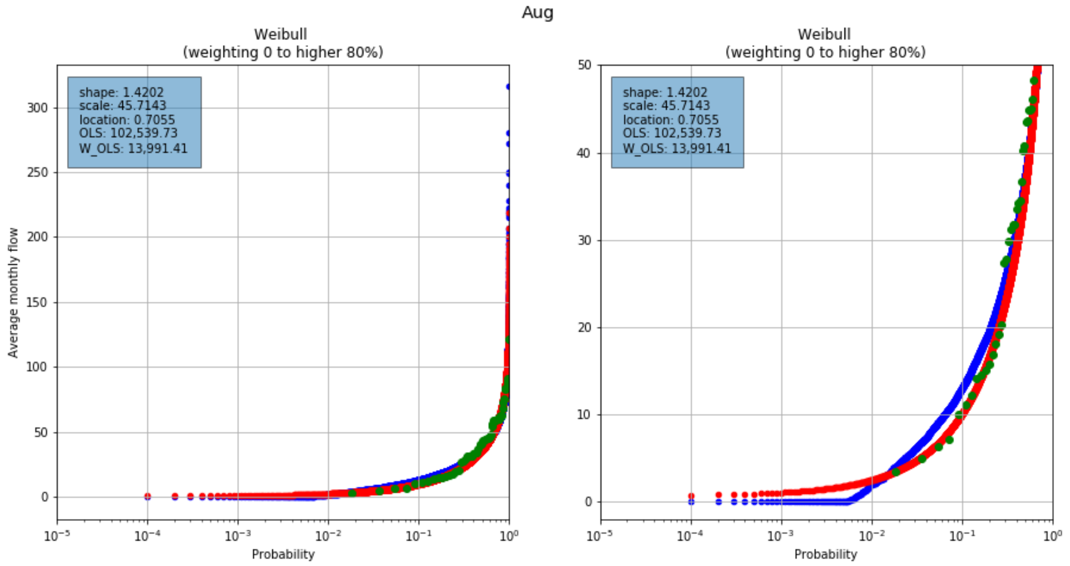


Figure 4-24 Weibull EVA Rainfall fit for 6 Months ending August (left) and September (right)

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

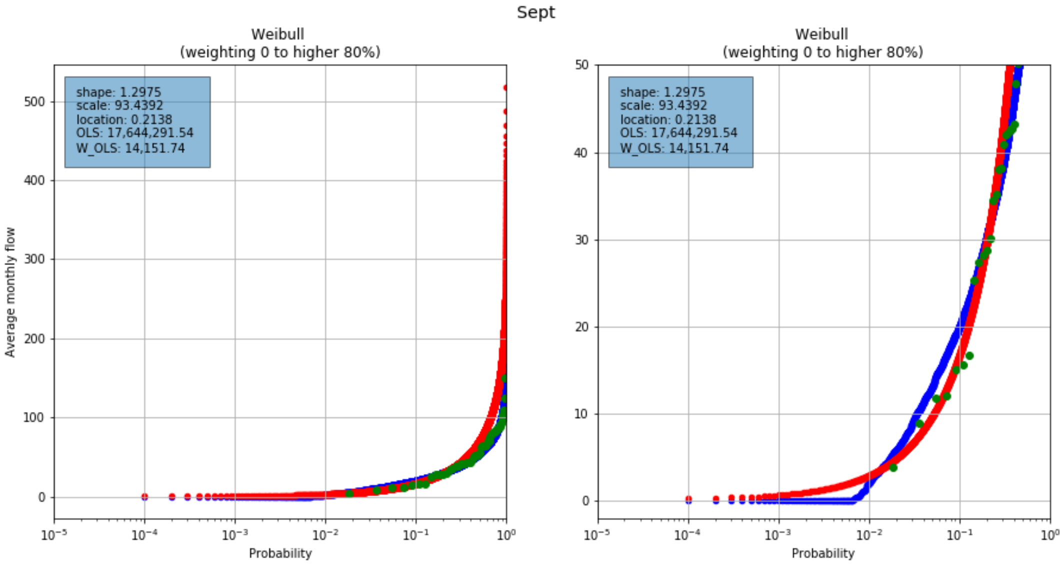


Figure 4-26 EVA Adjustment Developed for September

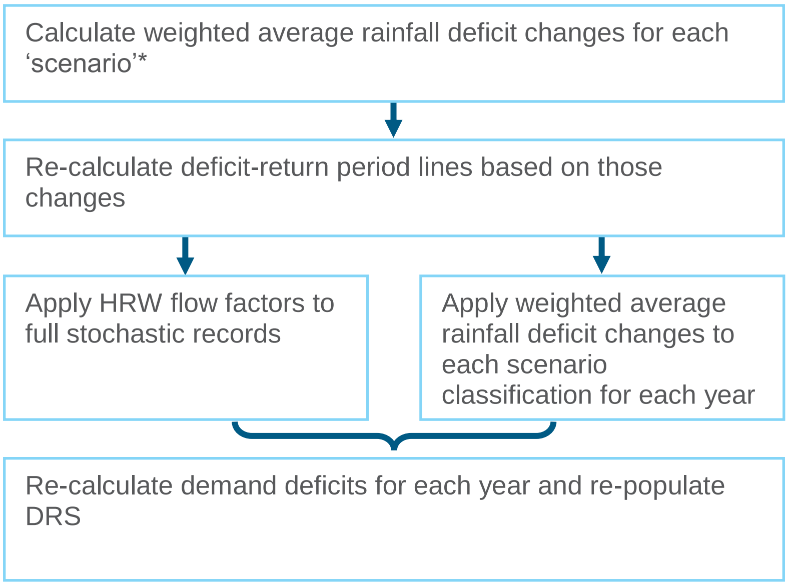
Daily flows were generated through monthly ‘nearest neighbour’ re-sampling of the historic record, which was scaled according to the generated stochastic flow.

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.

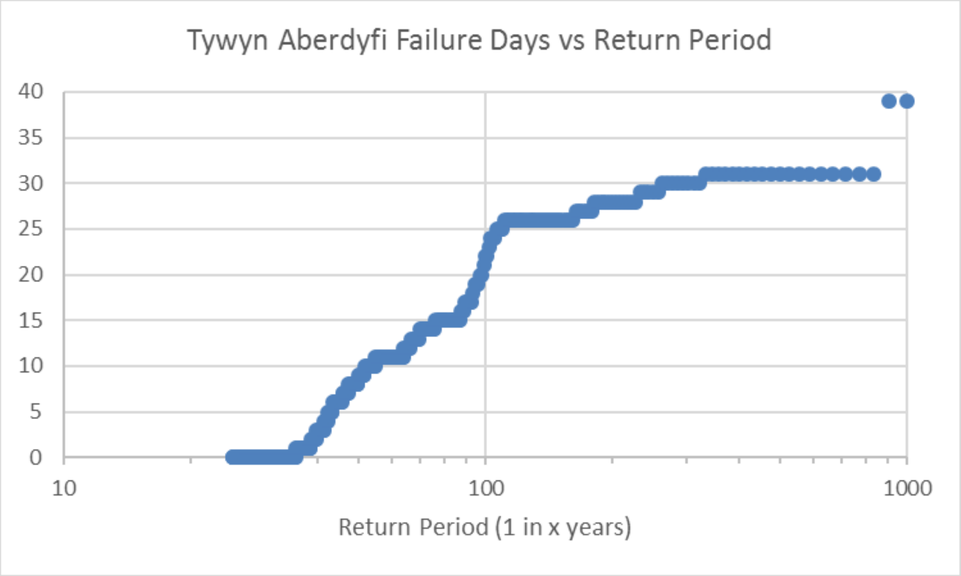


Figure 4-28 Failure Duration versus Probability Analysis for Tywyn Aberdyfi

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

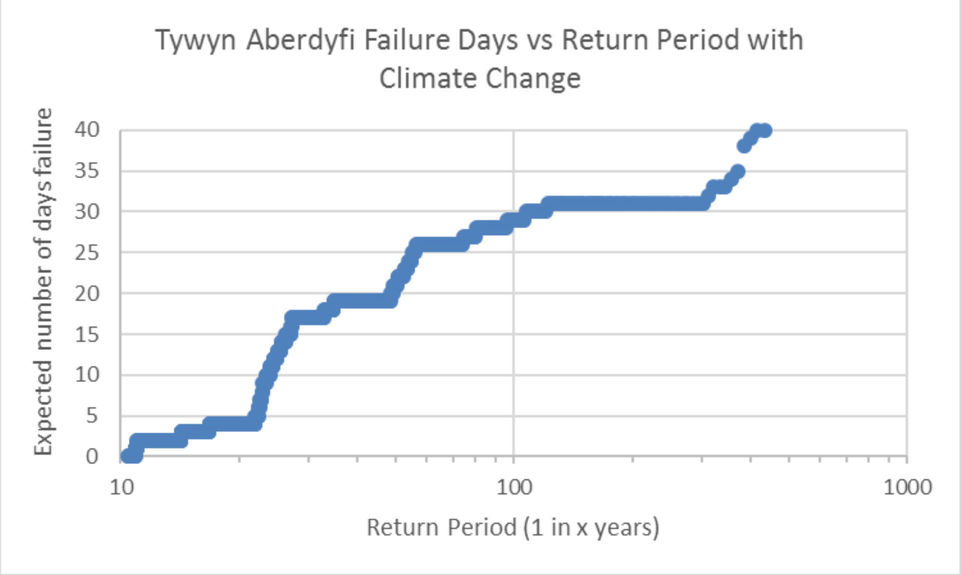


Figure 4-29 below.

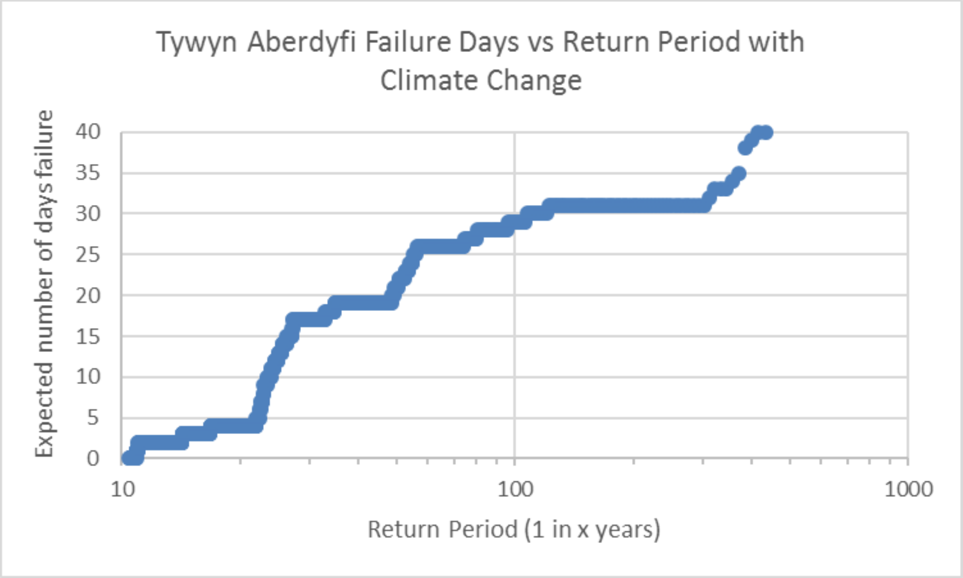


Figure 4-29 Failure Duration versus Probability Analysis for Tywyn Aberdyfi with 2030s climate change

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.

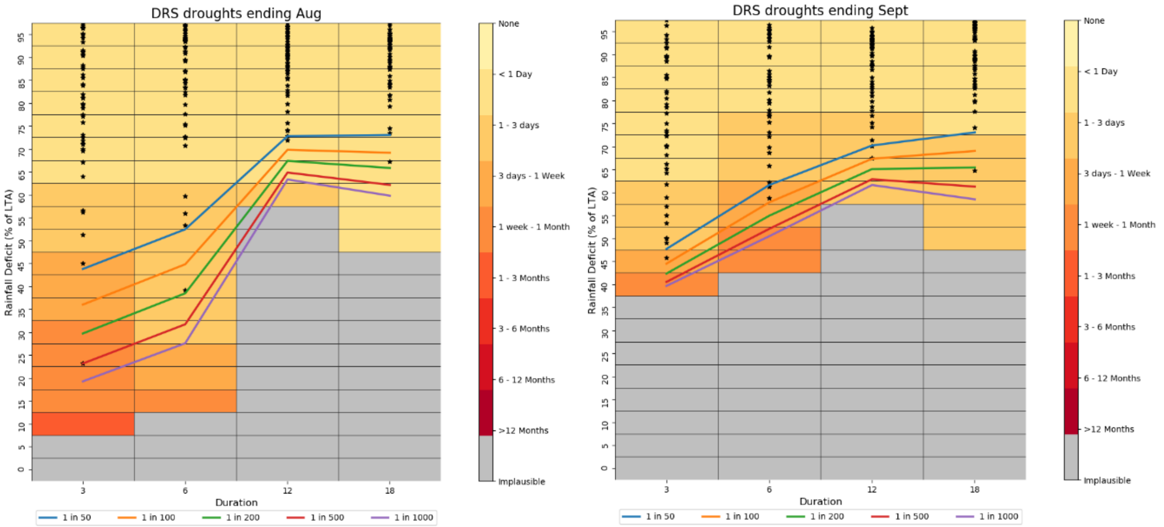


Figure 4-30 Baseline Generated Drought Response Surface

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).

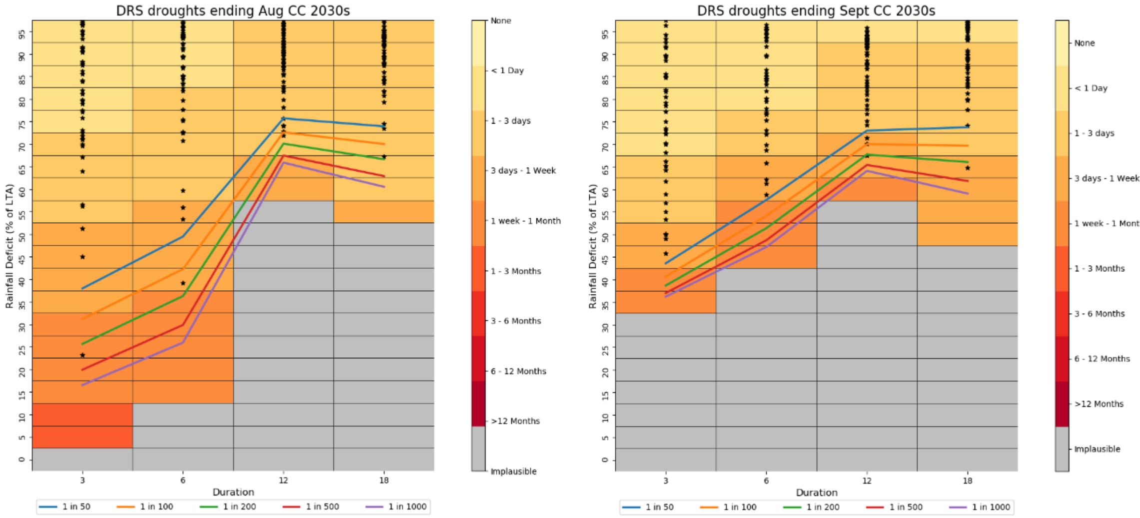


Figure 4-31 Generated Drought Response Surface with 2030s climate

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.

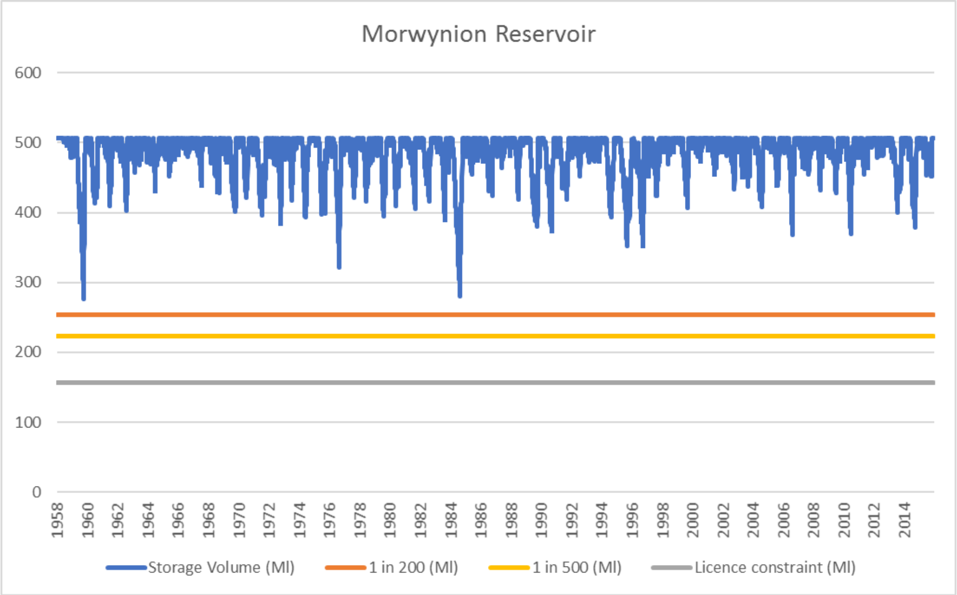


Figure 4-32 - Extreme Value Analysis results for Blaenau Ffestiniog (Morwynion Reservoir) showing new licence condition at 157 Ml

4.6. Barmouth and Lleyn Harlech

4.6.1. Key Modelling Assumptions

During the 2018 dry weather period stocks in Llyn 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 Llyn Eiddew Mawr and Llyn Tecwyn Uchaf (via Rhiw Goch and Cilfor WTWs respectively) to be transferred to the Barmouth WRZ to alleviate pressure on Bodlyn and prevent stocks crossing into the ‘drought action zone’. For the Drought Plan 2020 it was considered a better representation of operational behaviour to amalgamate both the 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.

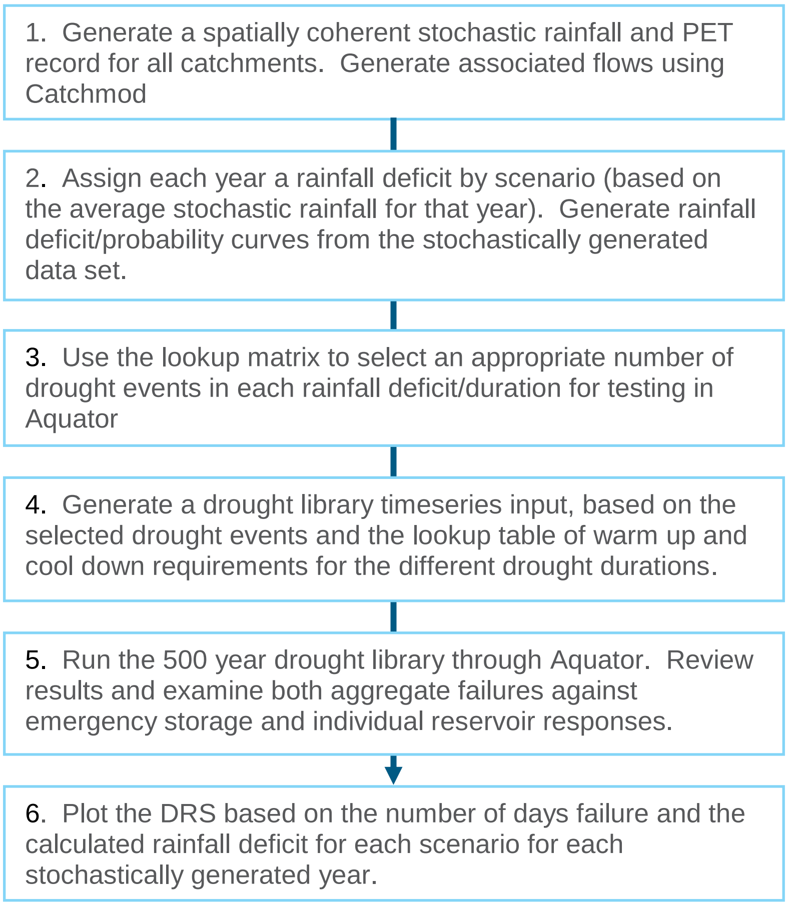
Therefore, the WRZs have been assessed here on a combined basis. The new Aquator model combining these WRZ was employed in place of the previous WRAPSim models. This work was undertaken by DCWW staff.

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)
Climate Change Scenario Used		The Barmouth WRZ WRMP UKCP09 50%ile scenario (7221) was applied globally in the combined WRZ model. It would have been inappropriate to use a combination of two different climate change scenarios in the model. As Bodlyn became the key focus of the assessment from a drought risk perspective, the Barmouth scenario was selected.

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 (Atkins, 2019).

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) were 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 (Atkins, 2019).

4.6.4. Methodology: 2030s Climate Scenario

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.

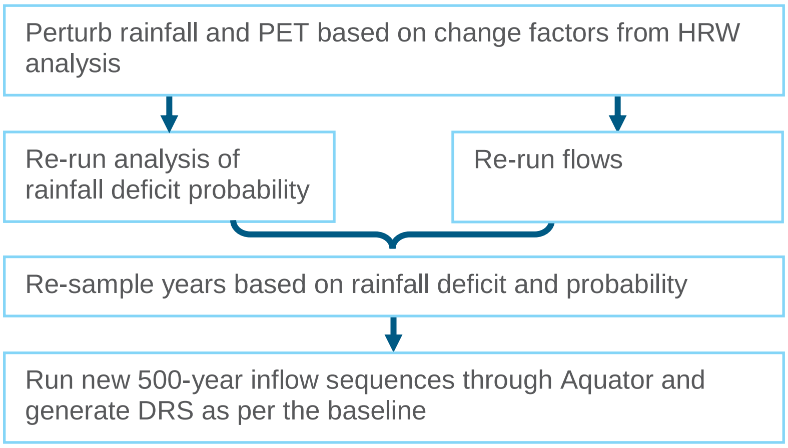


Figure 4-34 - Methodology for the Application of Climate Change

4.6.5. Results

Drought Risk Analysis

The Lleyn Harlech drought action zones are derived from the combined storage of Cwmystradllyn and Tecwyn Uchaf. Stocks in Cwm Dulyn and Eiddew Mawr aren’t considered for the drought action zones 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.

Whilst there were no simulated emergency storage failures in the Lleyn Harlech WRZ, there were a small number of failures at Llyn Bodlyn in the Barmouth WRZ. Most of the drought events leading to these failures had a return period of well over 1 in 500 years. One of the failures was associated with a 6 month drought event ending in September, with a return period of 1 in 80 years. However, this lasted for only one day, and could therefore easily be mitigated if it were to occur in reality and so did not require a DRS. With 2030s climate change impacts introduced, a greater number of failures (less than 1:500) were simulated although there is some uncertainty around the validity of these and further work is needed to ensure that the new combined WRZ Aquator model is behaving appropriately. For the Draft Drought Plan, DCWW has chosen not to present a DRS but once the results of further testing confirm if there are any failures simulated in the baseline or climate change scenarios then corresponding DRS will be generated. This work will be completed in time to inform the Final Drought Plan 2020.

4.7. Tywi CUS

4.7.1. Key Modelling Assumptions

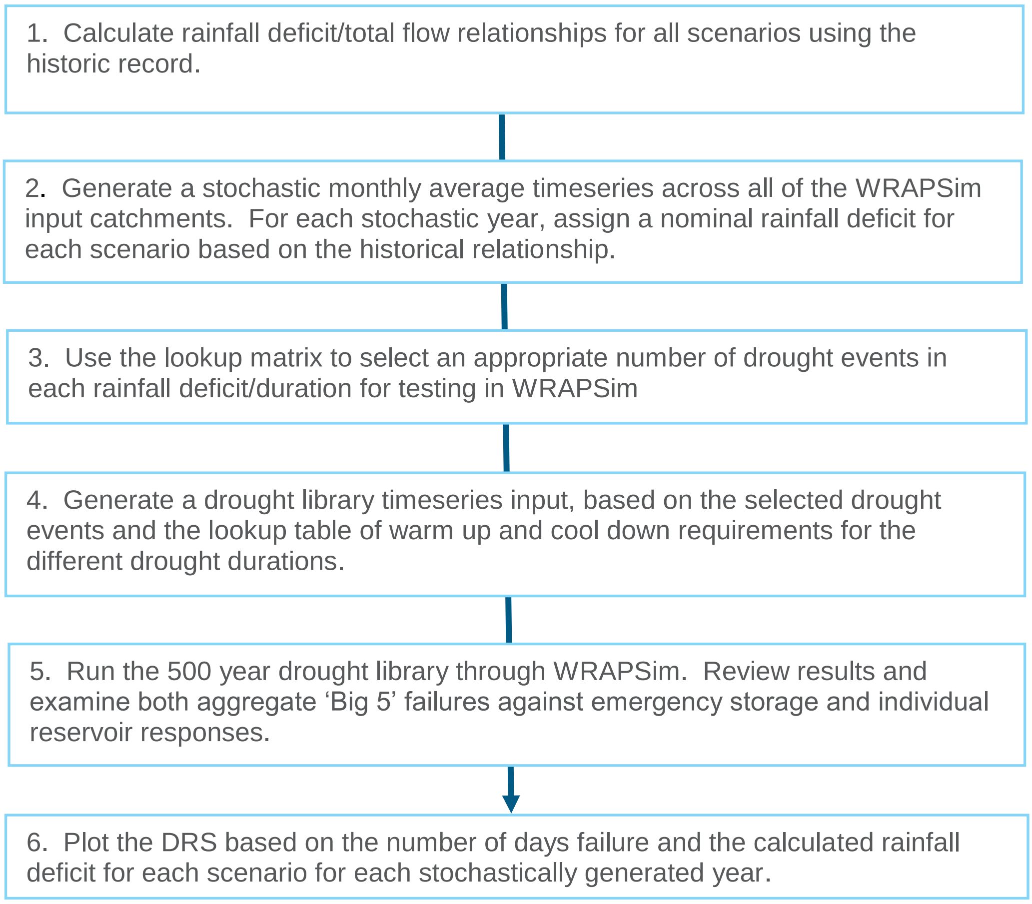
The Tywi Gower Conjunctive Use System (CUS) is a large WRZ whose water supply is from a combination of four impounding reservoirs and two river abstractions, which are operated conjunctively to generate the yield. Due to the relatively complex nature of the water resource arrangement it was necessary 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))
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 4-35 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 4-35 - 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 4-36.

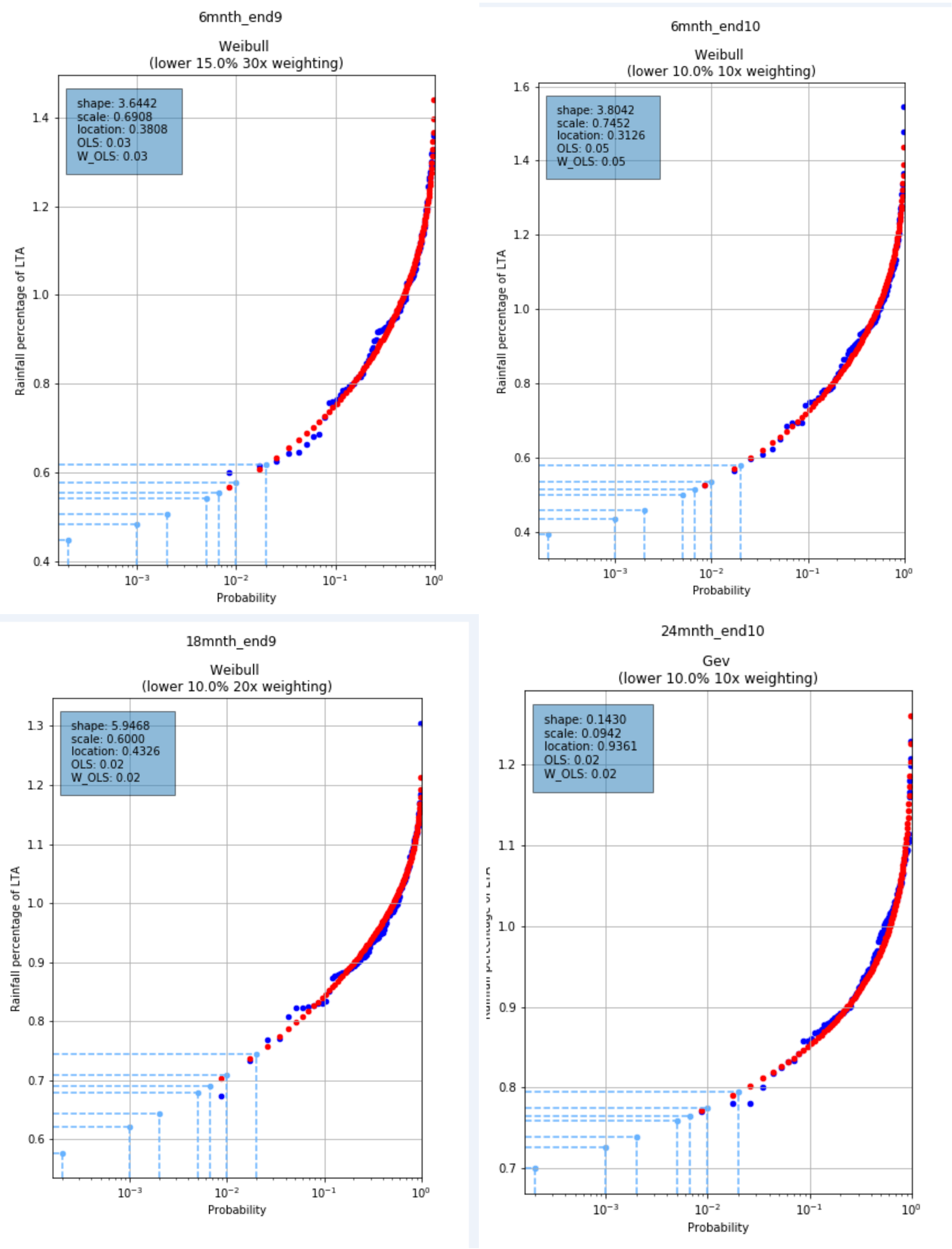
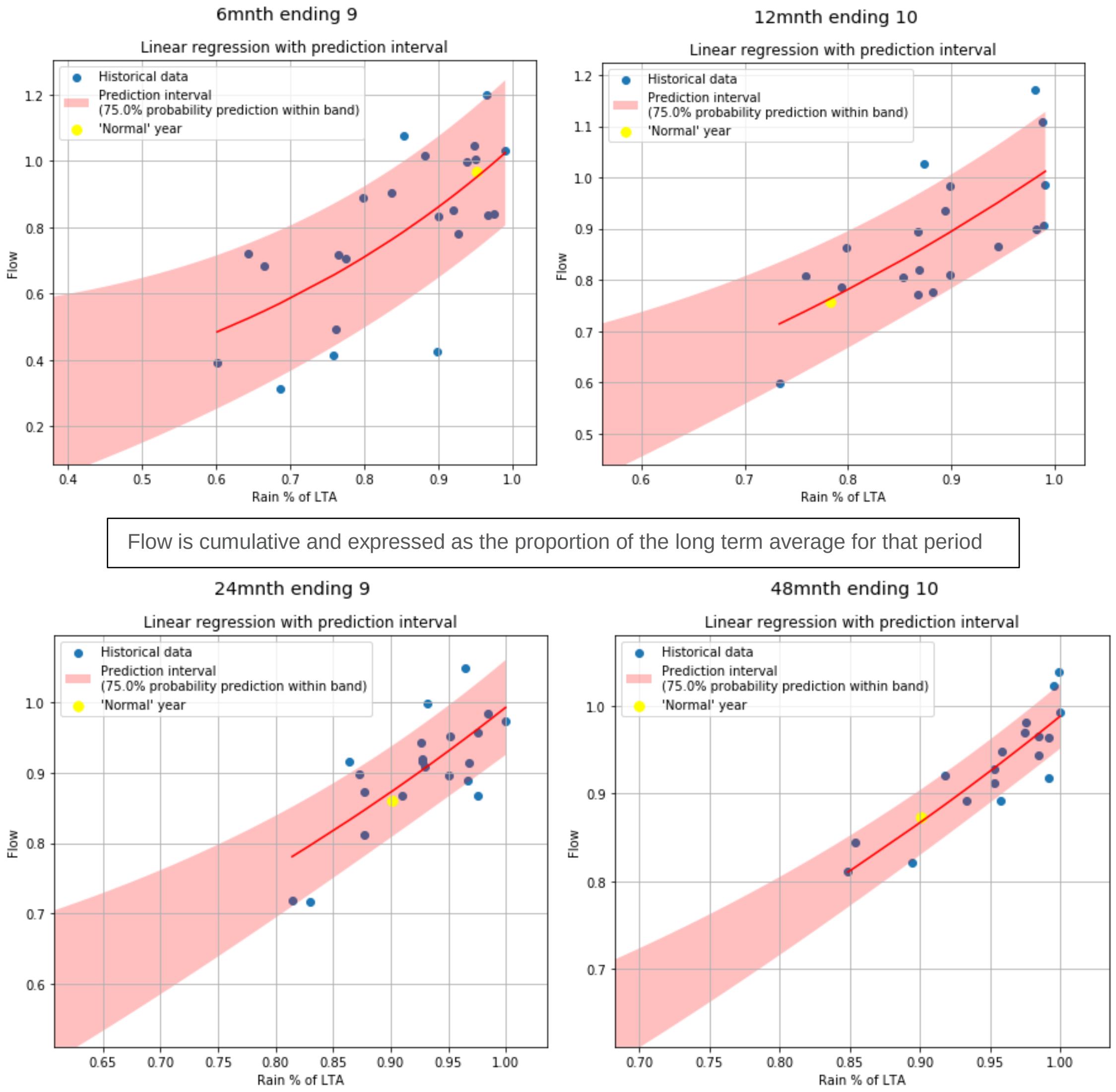


Figure 4-36 - Example EVA Plots for Tywi CUS

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 4-37.

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.



Flow is cumulative and expressed as the proportion of the long term average for that period

Figure 4-37 - 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.

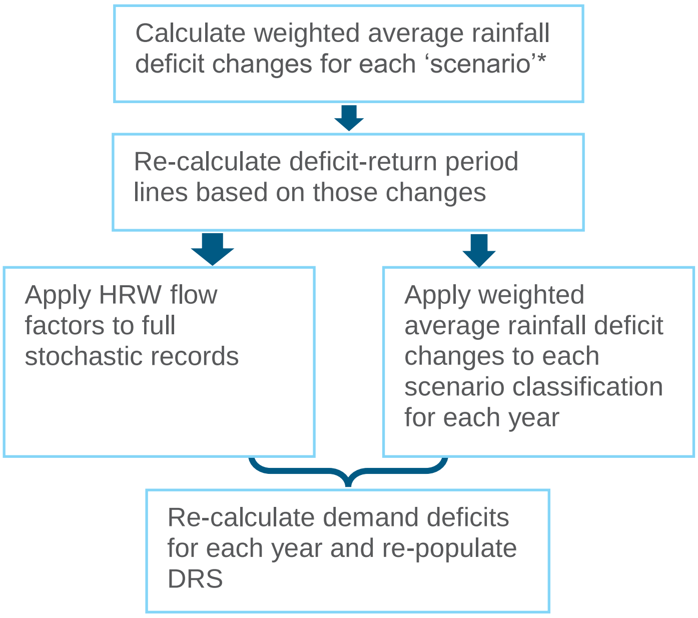
Stage 4: Generation of Flows for the Drought Library

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 4-38.



** 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 4-38 - 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 4-41 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.

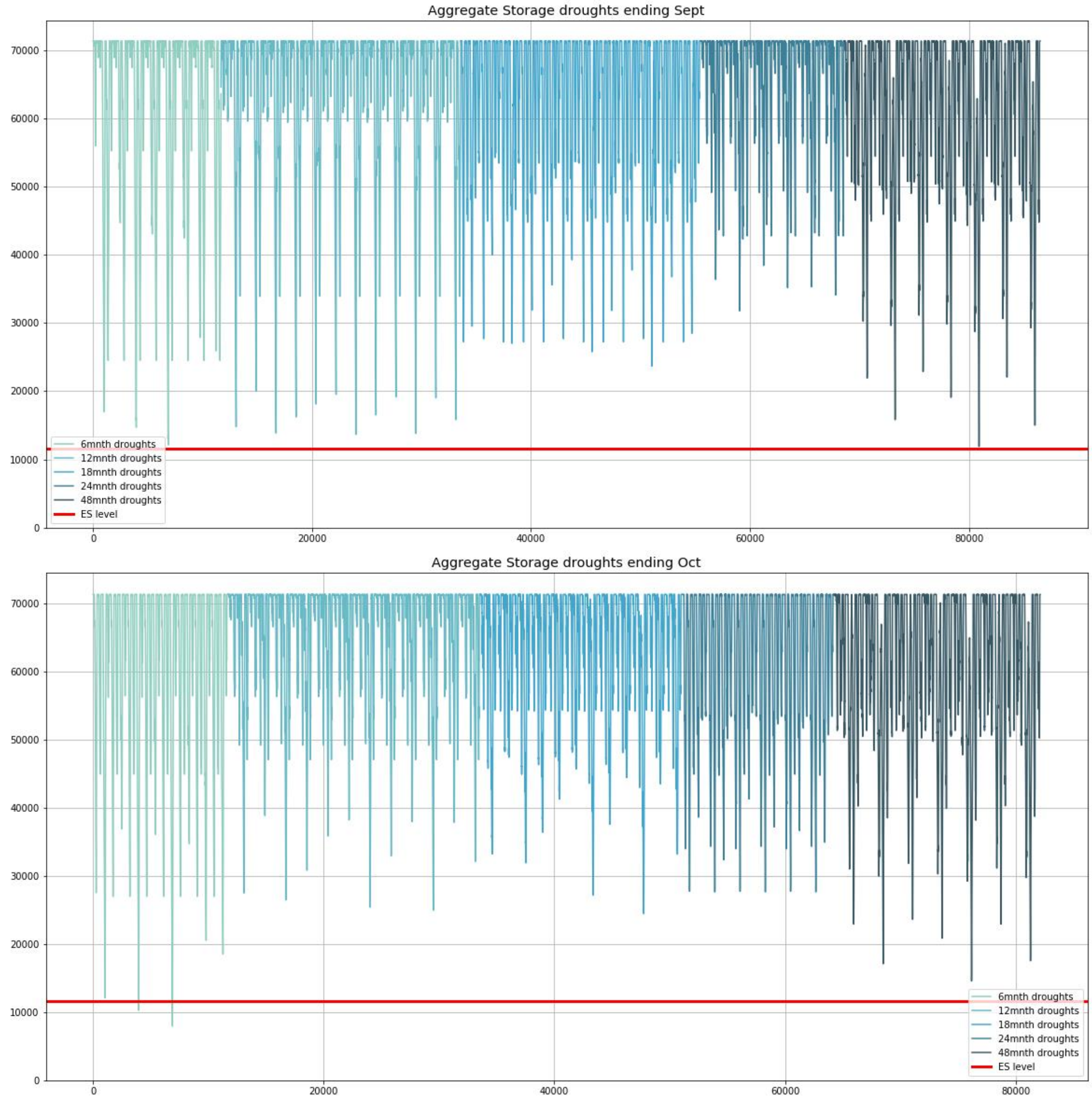


Figure 4-39 - Aggregate Storage Plots for baseline scenario

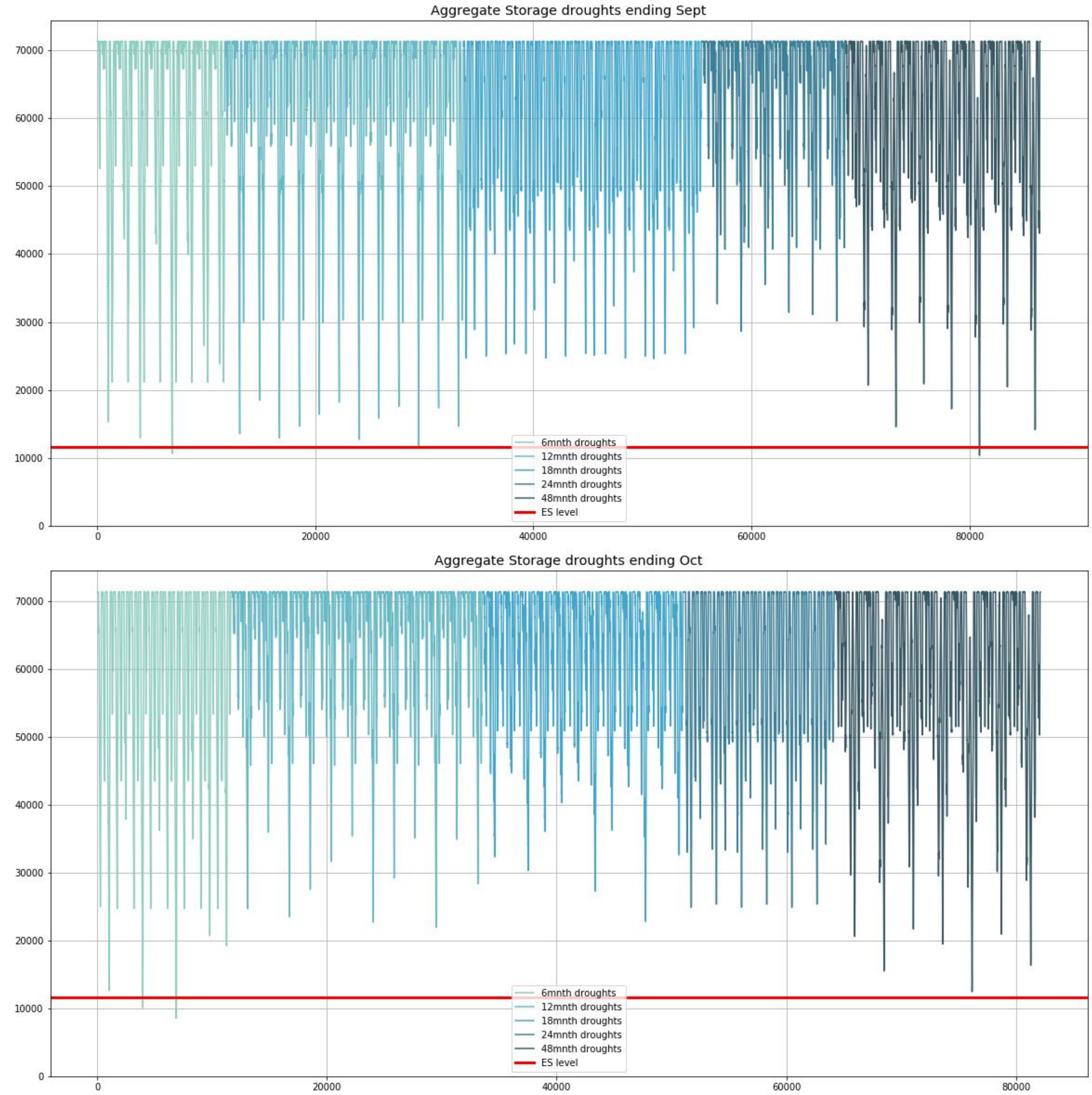


Figure 4-40 - Aggregate Storage Plots for 2030s Climate change scenario

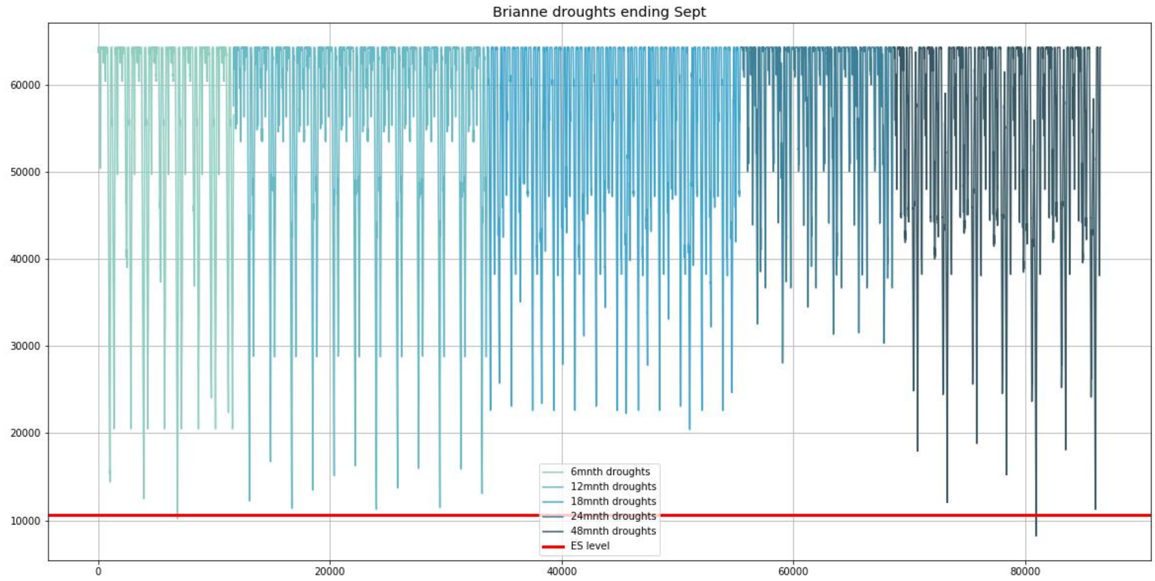


Figure 4-41 – Llyn Brianne Storage Plots for baseline scenario

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 4-40 does not appear in the corresponding DRS (Figure 4-43). 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.

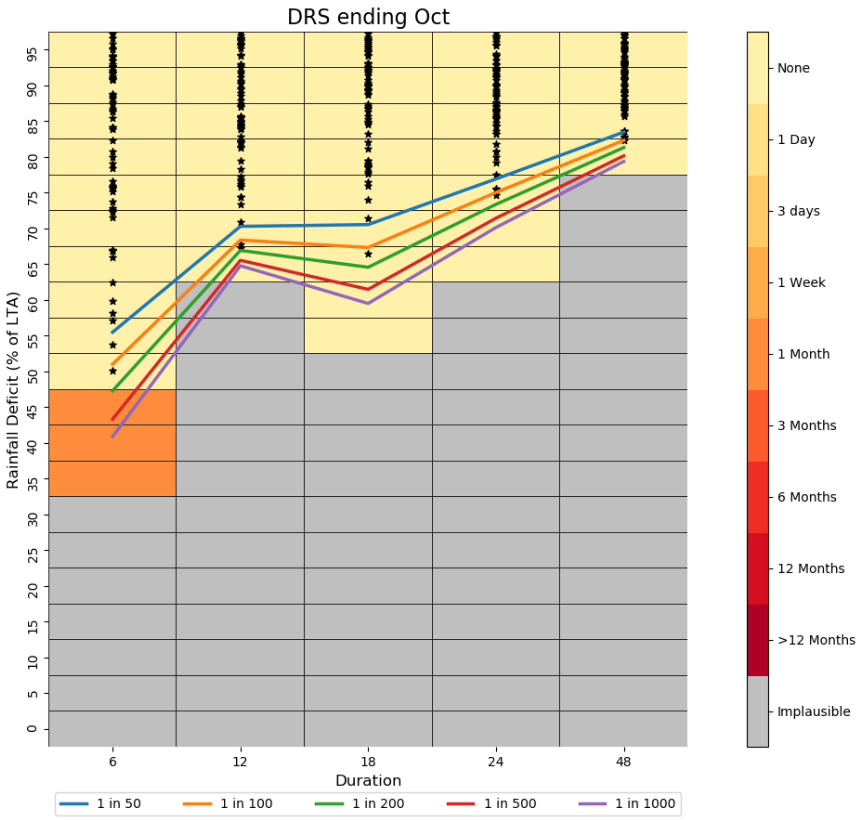


Figure 4-42 Baseline Generated Drought Response Surface (droughts ending October)

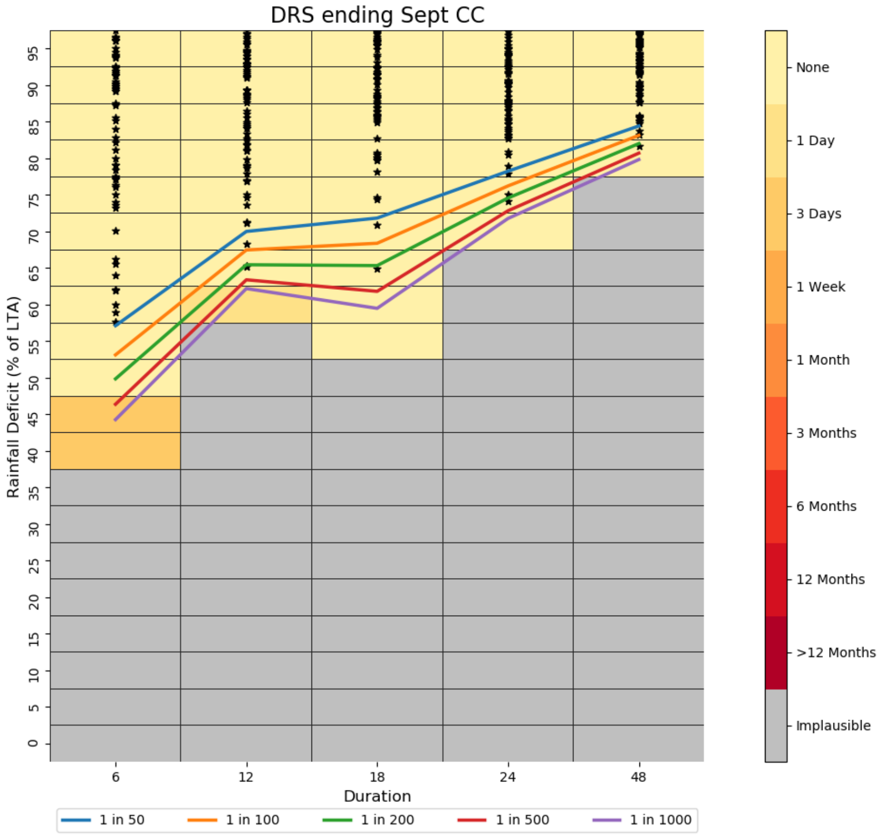


Figure 4-43 Generated Drought Response Surface with 2030s climate (droughts ending September)

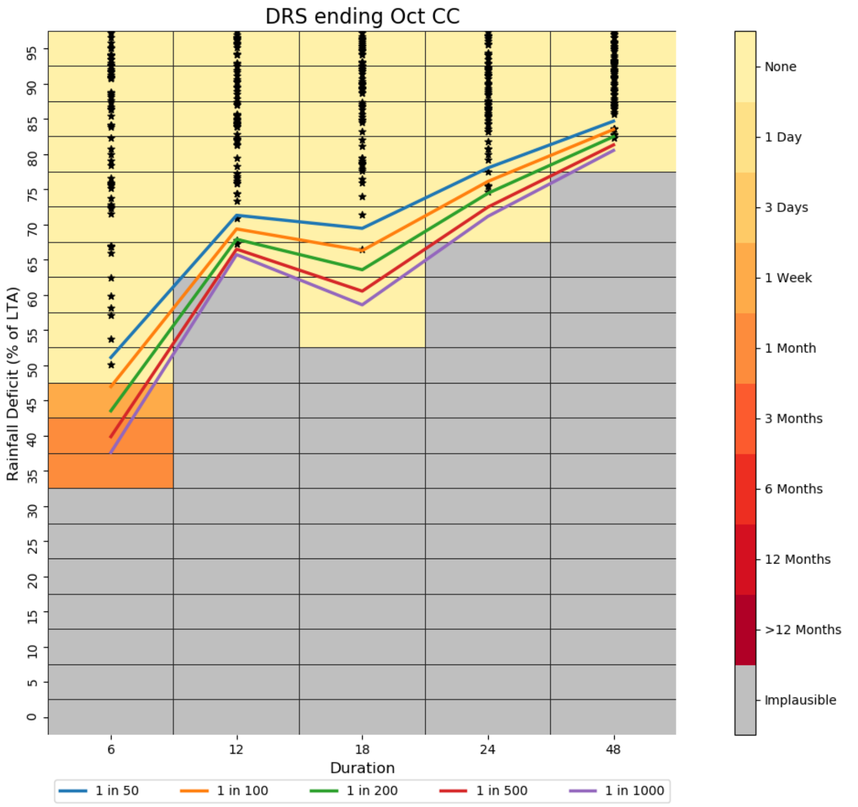


Figure 4-44 Generated Drought Response Surface with 2030s climate (droughts ending October)

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 (Atkins, 2019) 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.

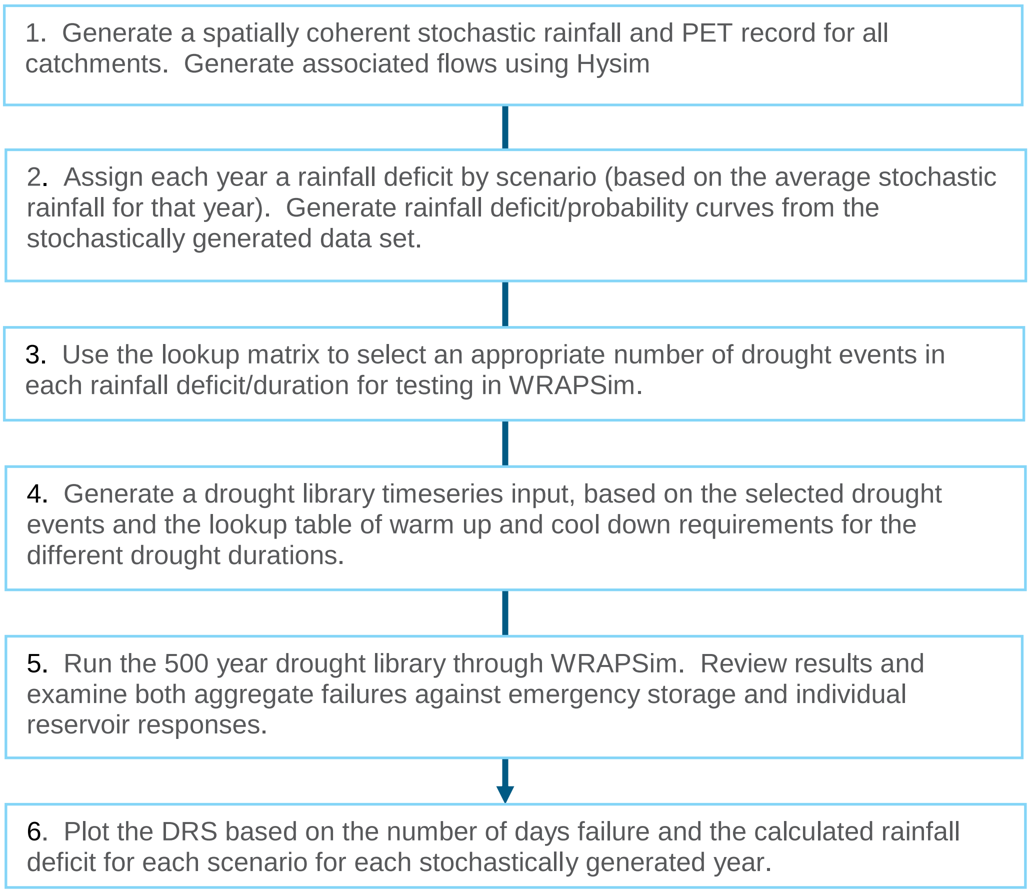
Table 4-9 - Summary of Key Modelling Assumptions

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 4-45 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 4-45 - 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 4-46. 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.

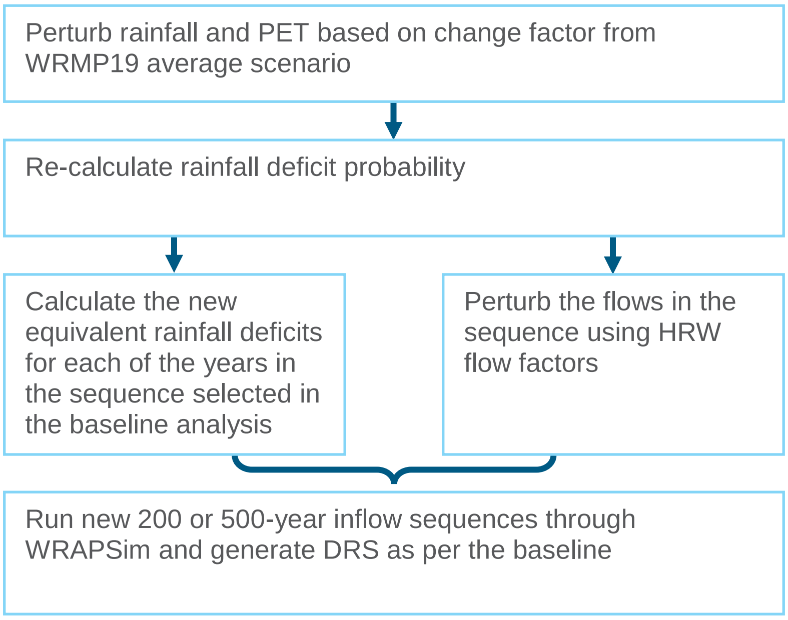


Figure 4-46 - Summary of Climate Change Methodology

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 4-47 and for aggregated storage in Figure 4-48.

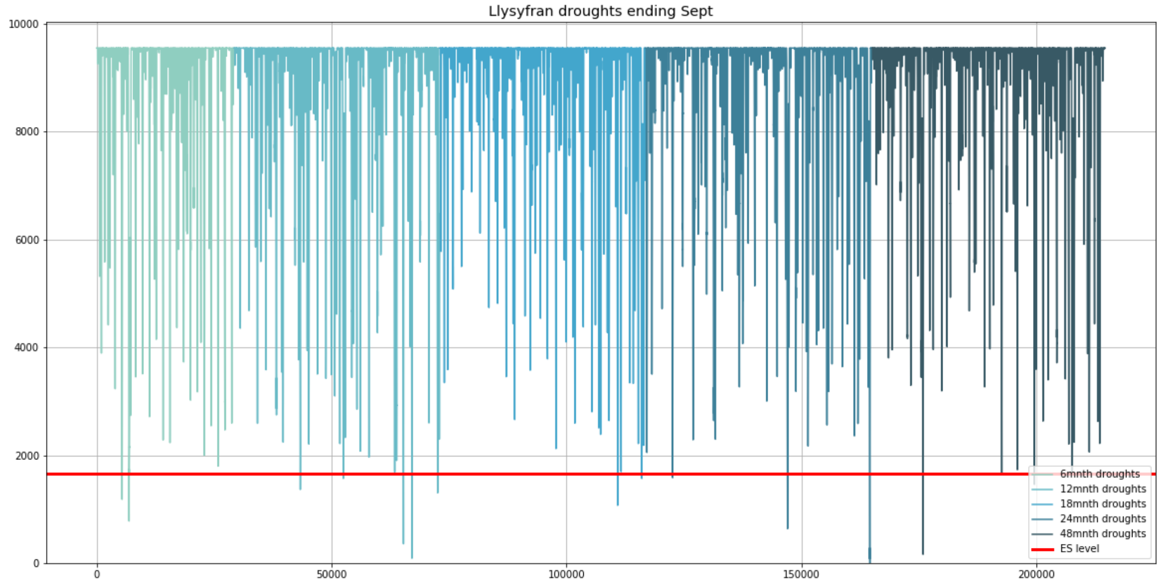


Figure 4-47 - Example of the Drought Library Timeseries for Llys-Y-Fran Reservoir (Model 5N baseline, droughts ending September)

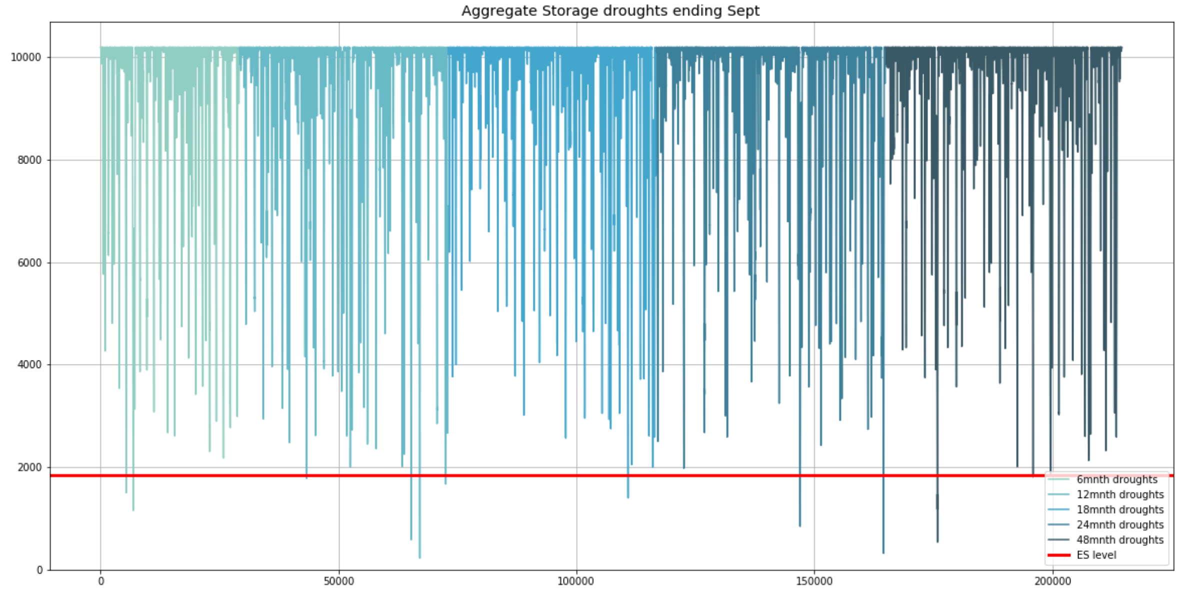


Figure 4-48 - Example of the Drought Library Timeseries for aggregated storage (Model 5N baseline, droughts ending September)

Drought Response Surfaces

As shown in Figure 4-49, 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.

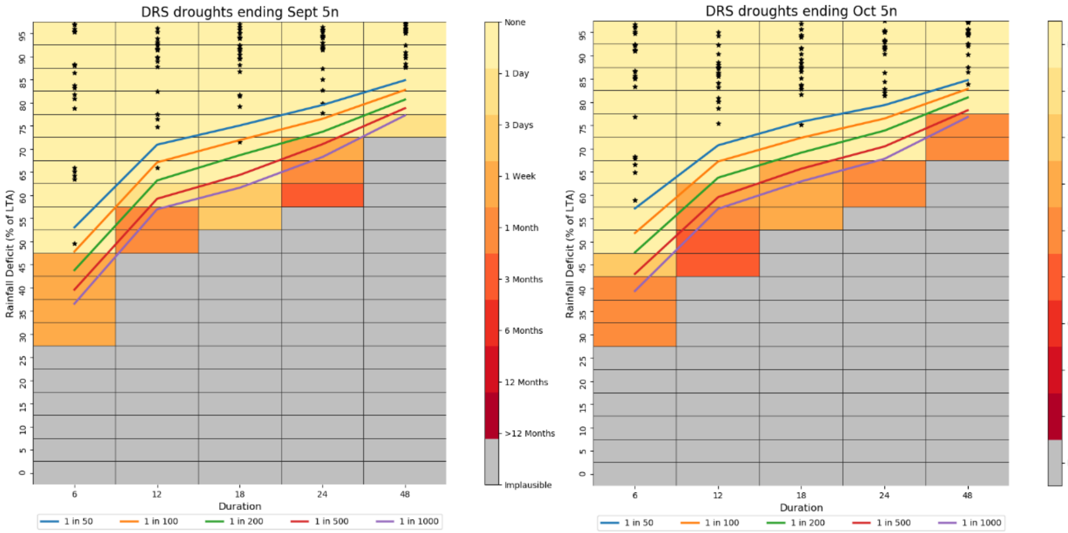


Figure 4-49 - Baseline DRS for Model Setup 5N

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 4-50 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.

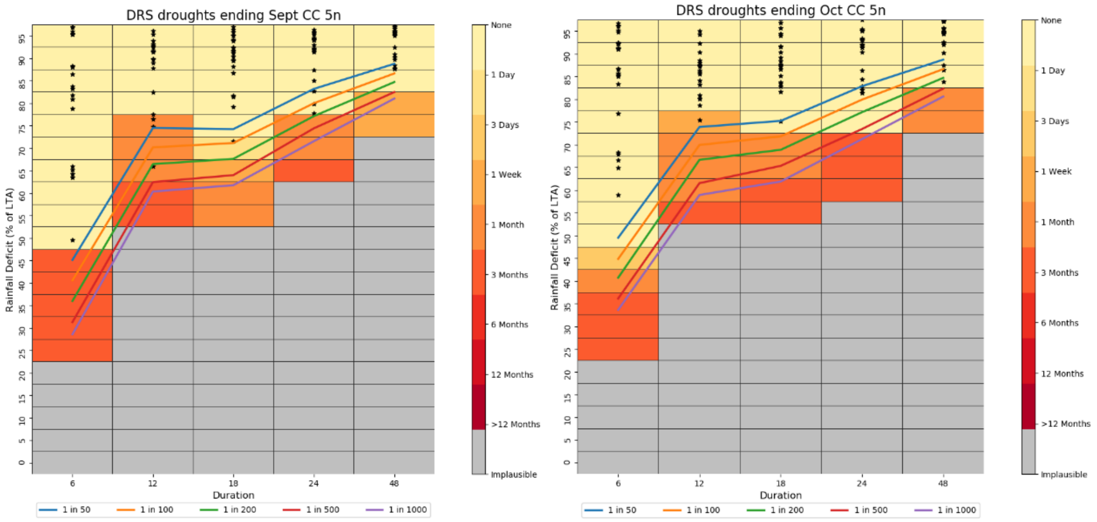


Figure 4-50 - 2030s Climate DRS for Model Setup 5N

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.

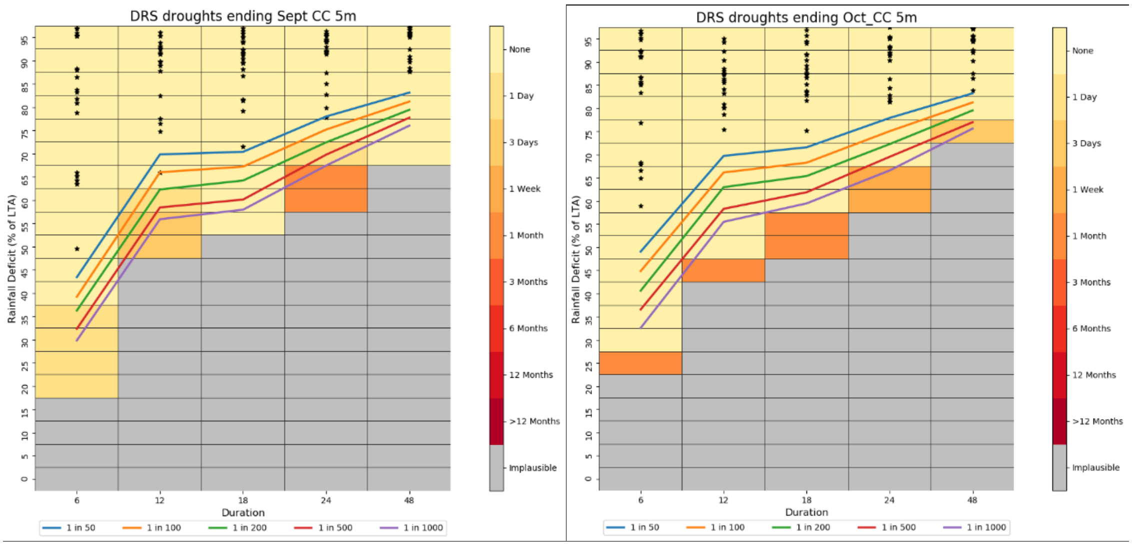


Figure 4-51 - 2030s Climate DRS for Model Setup 5M

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 4-52 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 4-70, 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.

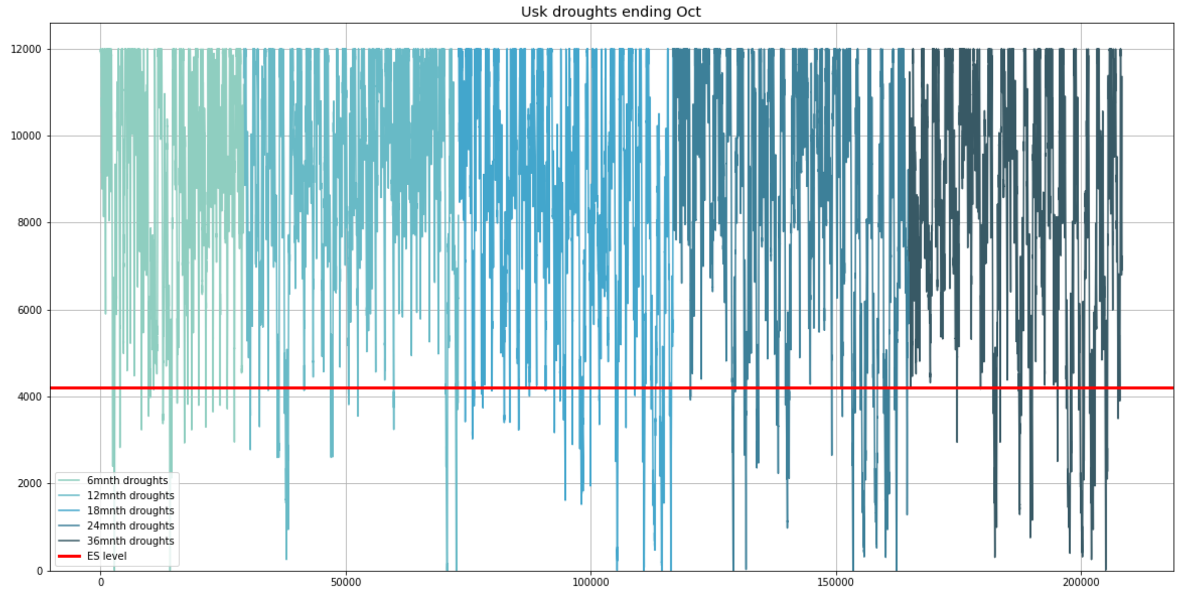


Figure 4-52 – Baseline Usk Storage Plots (droughts ending October)

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

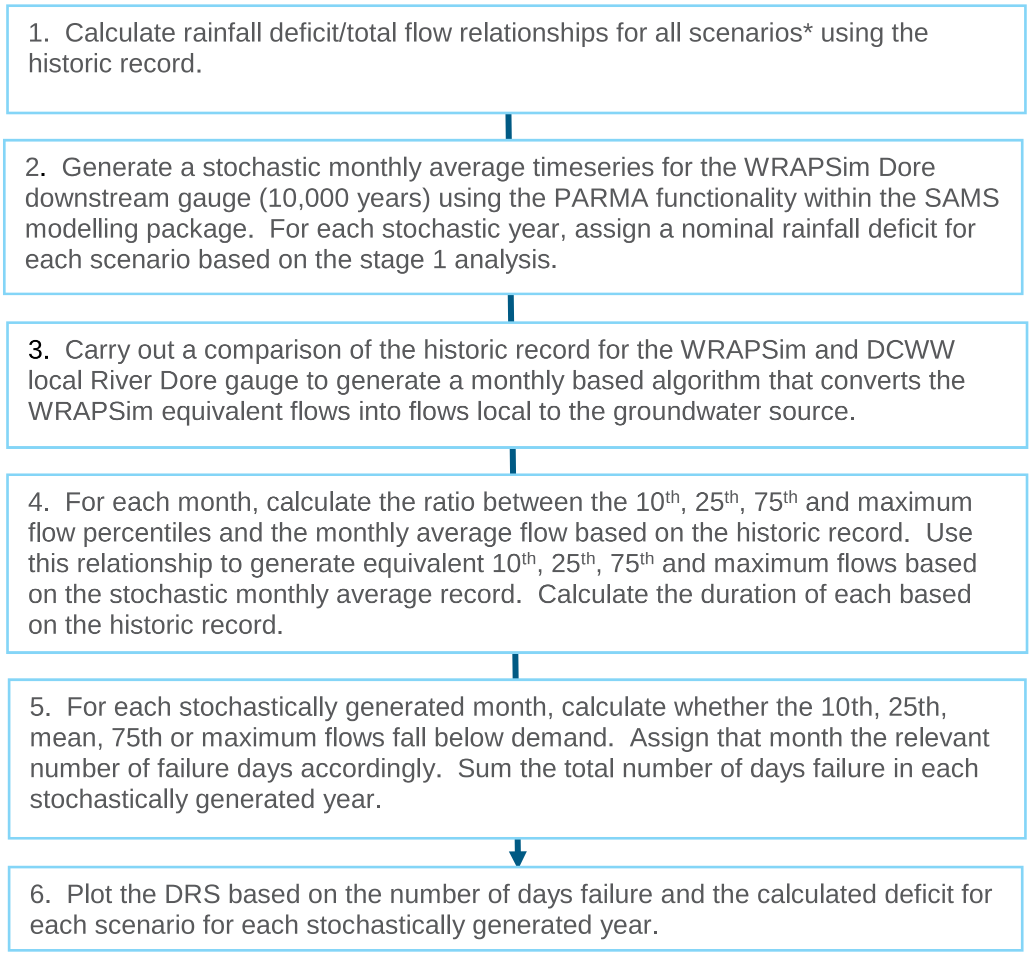
Parameter	Value(s) Used	Comments/Notes
Demand Level Analysed	2.5 Ml/d DYAA	Based on DI, plus Target Headroom, plus outage, process and raw water losses. Demand profile based on WRAPSim.
Durations Analysed	3, 6, 12, 18 months	Small catchment with limited baseflow; analysis is focused on low flow durations
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 4-53 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 4-53 - 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 4-54 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.

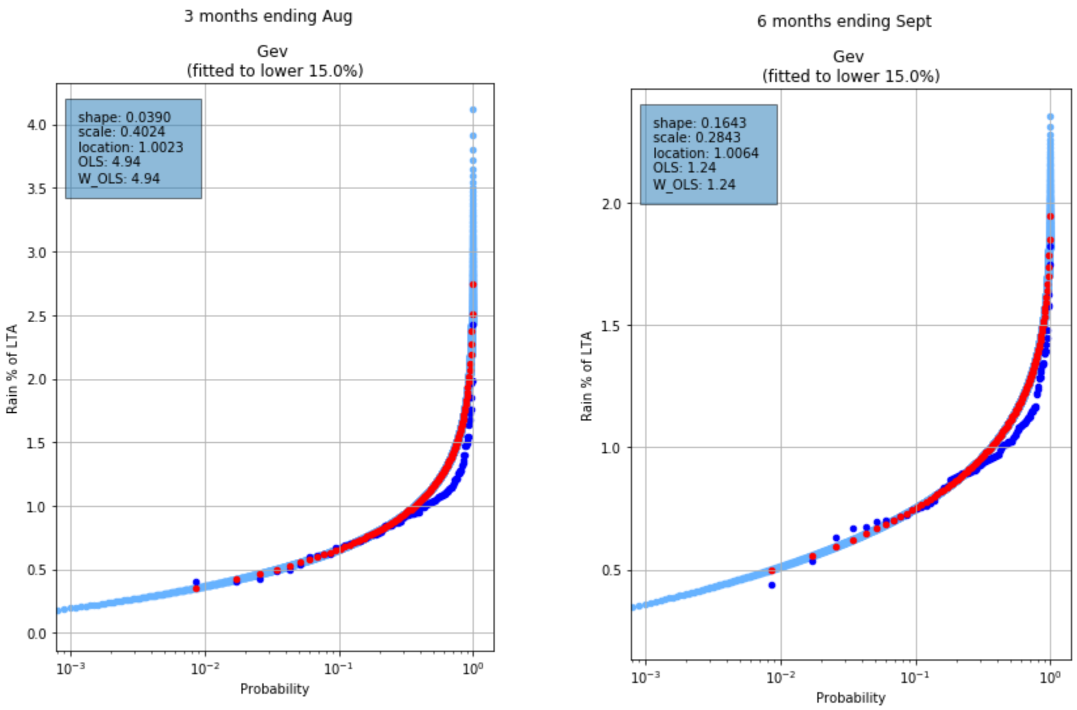


Figure 4-54 - Examples of the Final GEV Plots for Rainfall

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 4-55 below.

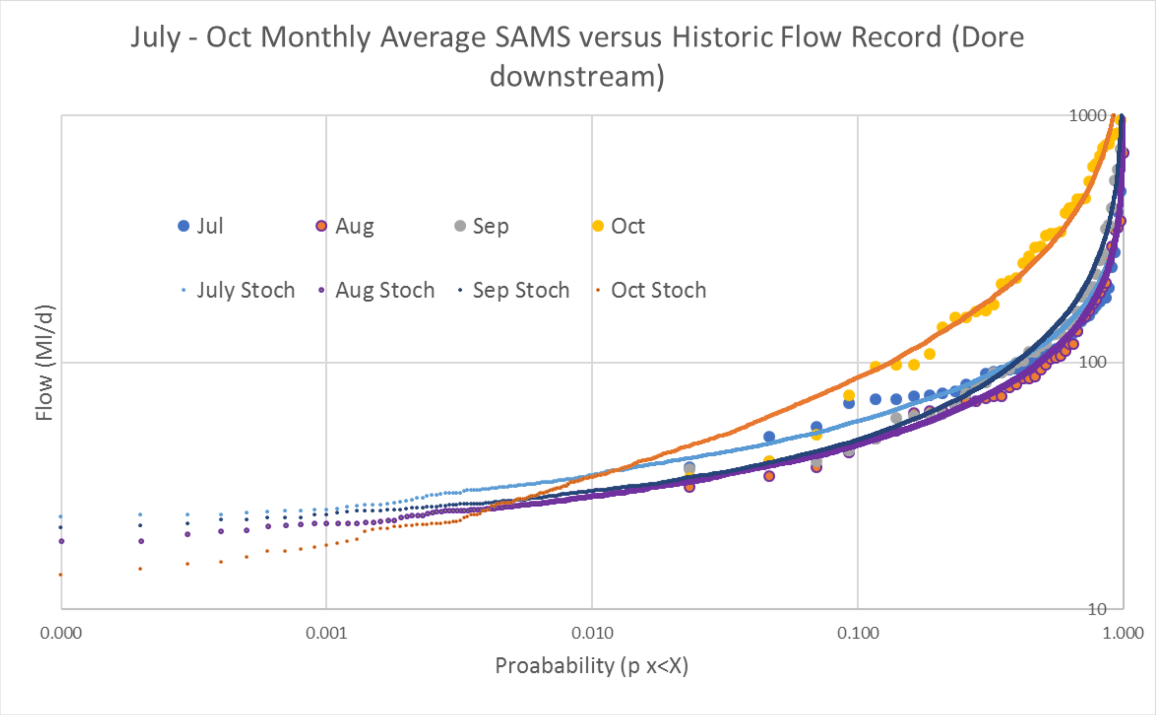


Figure 4-55 - Historic Record versus SAMs Generated Flow (Dore downstream gauge)

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 4-56 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.

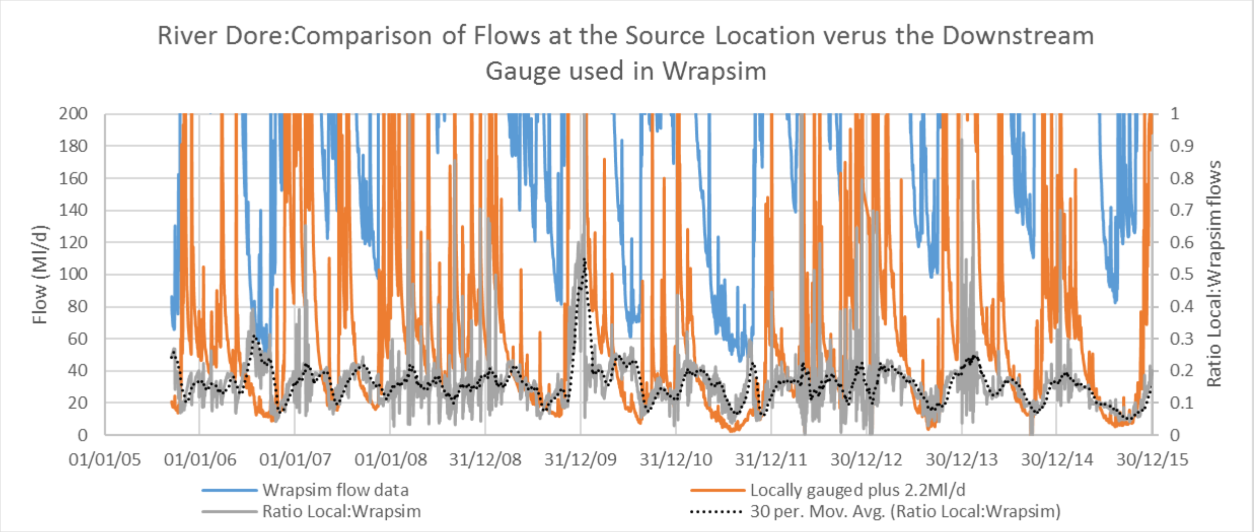


Figure 4-56 - Comparison of Gauging Sites on the River Dore

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 4-57 below.

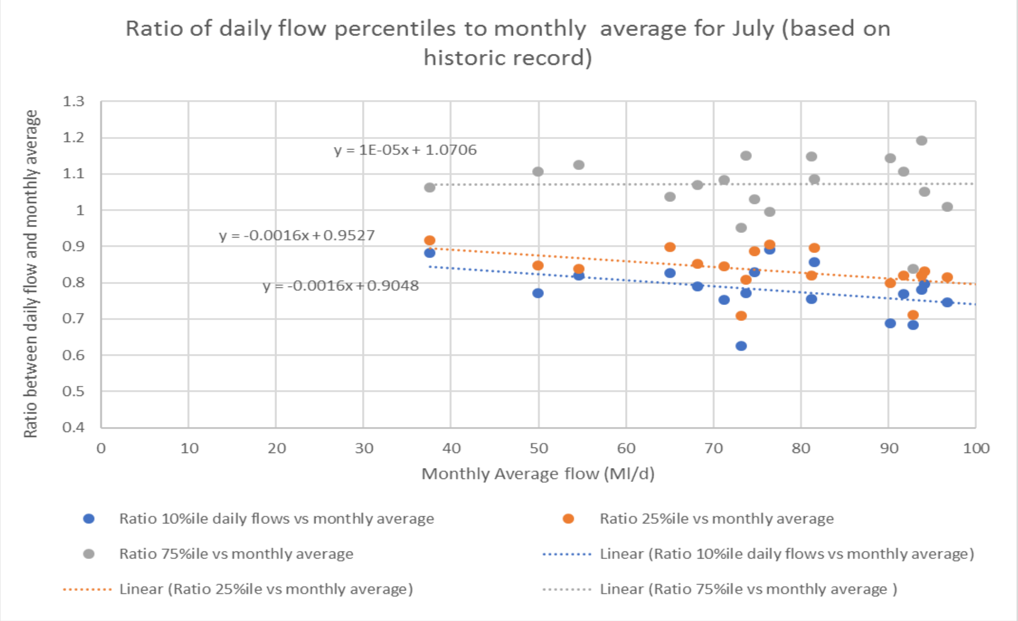


Figure 4-57 - Example Percentile Ratio Output

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:

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

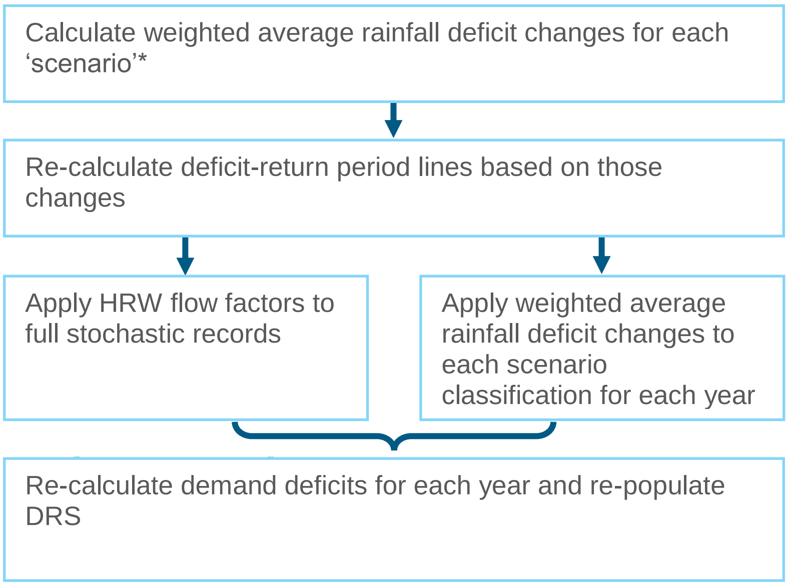
Where:

- 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 4-58.



** 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 4-58 - 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 4-59 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.

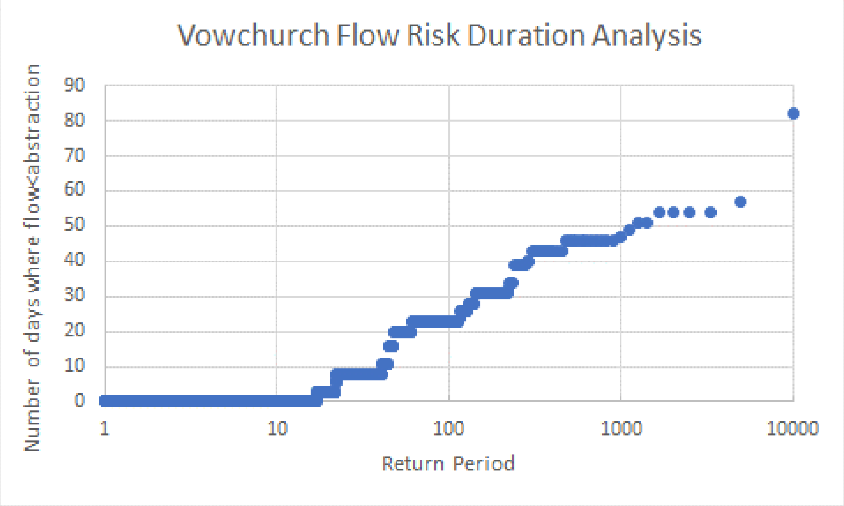


Figure 4-59 - Supply Risk Analysis without Climate Change

The impact from climate change on the probability-duration failure analysis is shown in Figure 4-60 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.

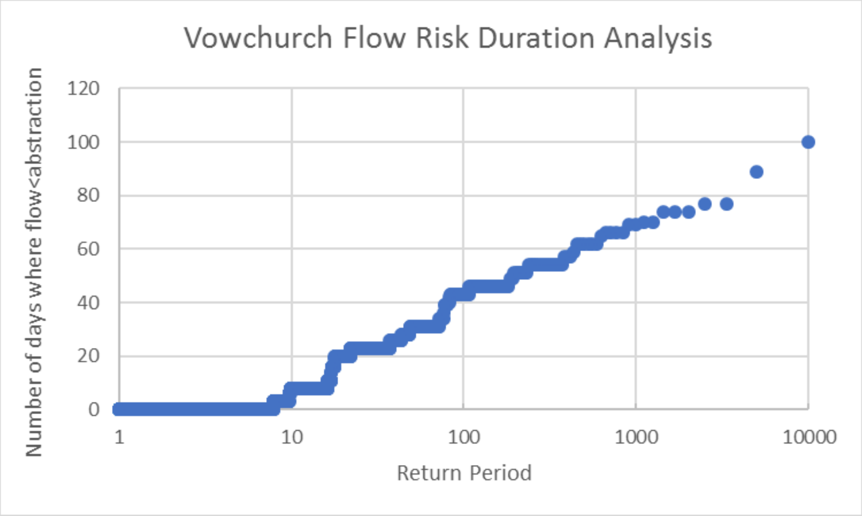


Figure 4-60 - Supply Risk Analysis with 2030s Climate Change

Drought Response Surfaces

The DRS with and without climate change are provided in Figure 4-61 and Figure 4-62 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).

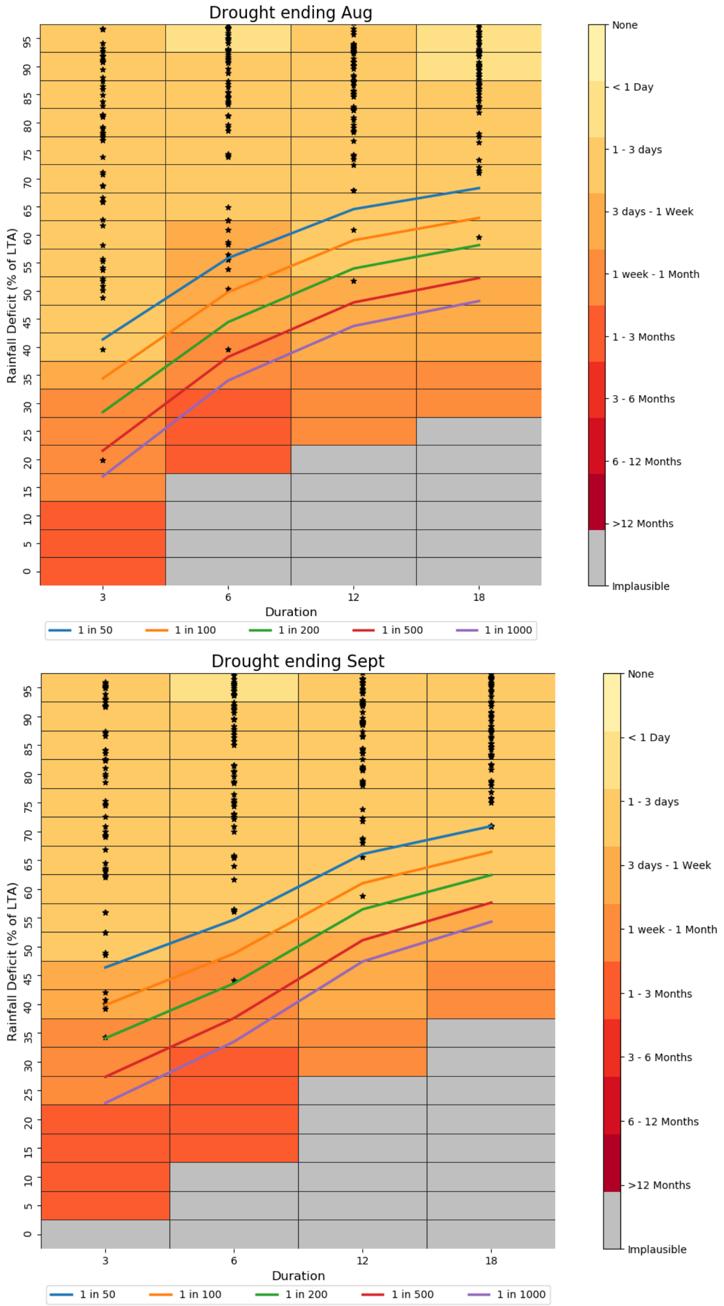


Figure 4-61 - Drought Response Surfaces for Baseline

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 4-62. 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.

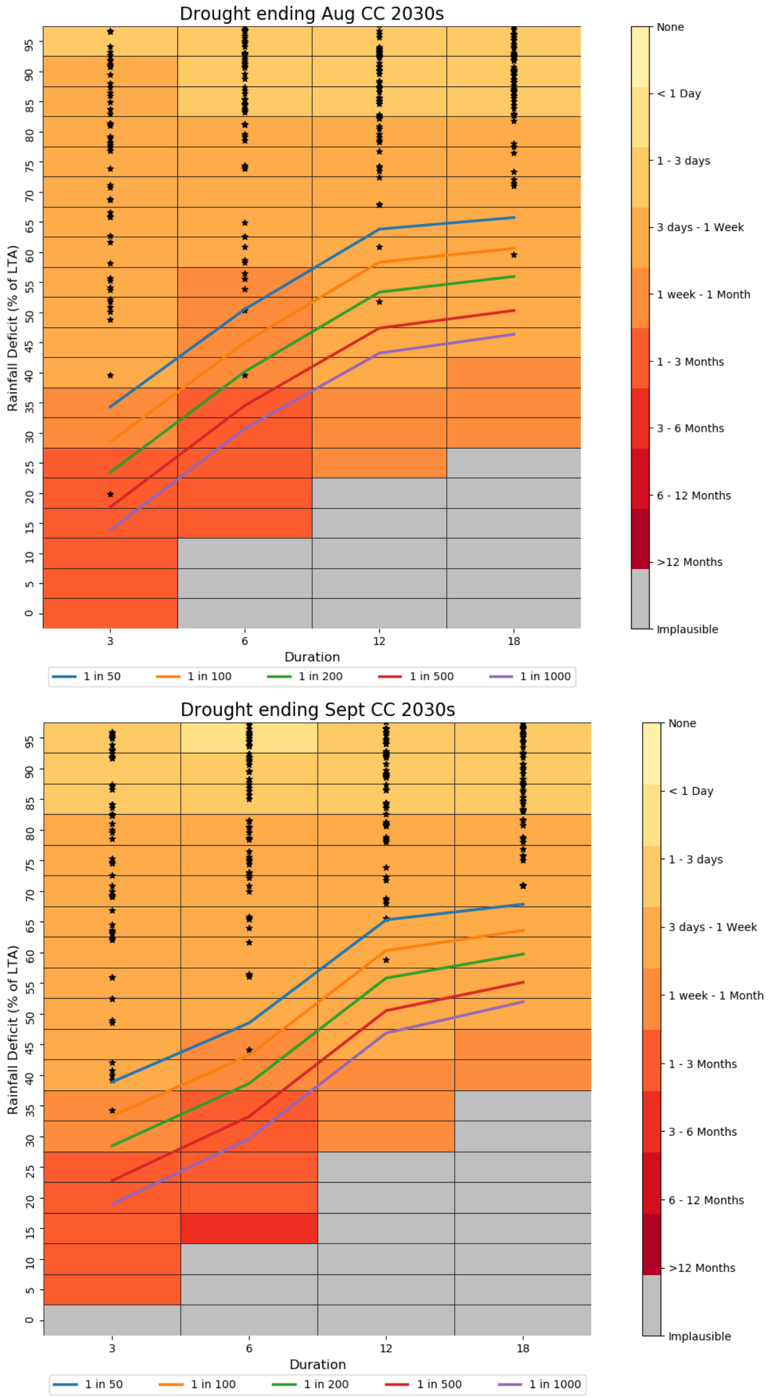


Figure 4-62 - Drought Response Surfaces for 2030s climate

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 4-63 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 4-63 - 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 4-64 below.

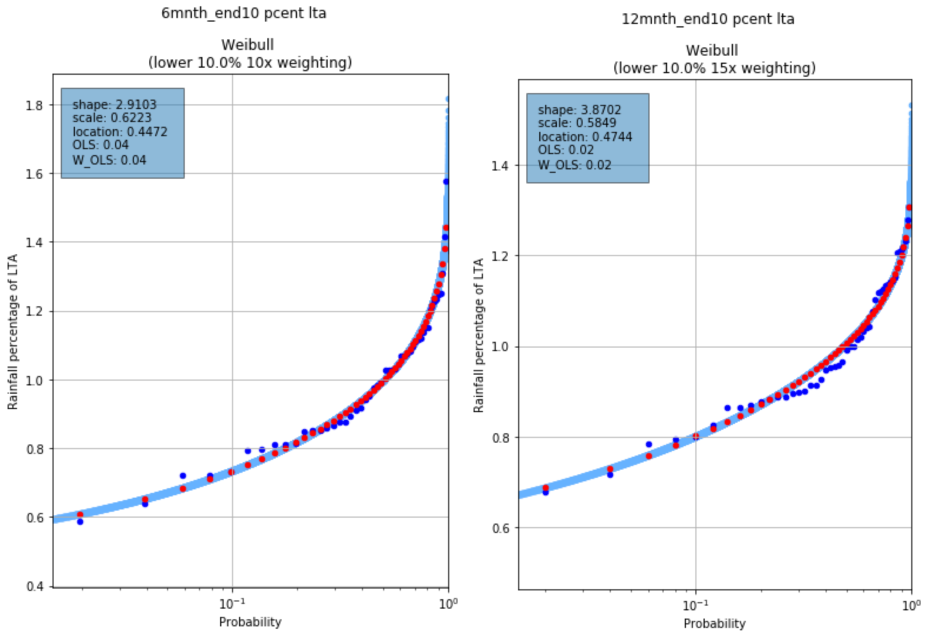


Figure 4-64 - Examples of the Final EVA Plots for Rainfall

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.

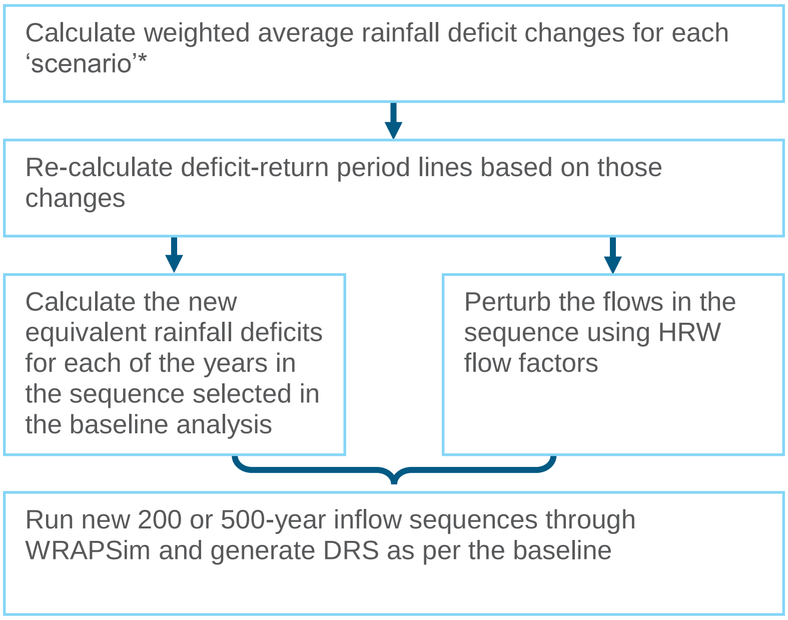
The number of droughts involved was purely a pragmatic decision that balanced the need to fully explore the drought risk in each cell against the run times involved in WRAPSim. As shown, all events up to 1 in 1000 years had at least 4 droughts explored for each combination of rainfall severity and duration, 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 4-65.



** 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 4-65 - 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 4-67). 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 4-67 below.

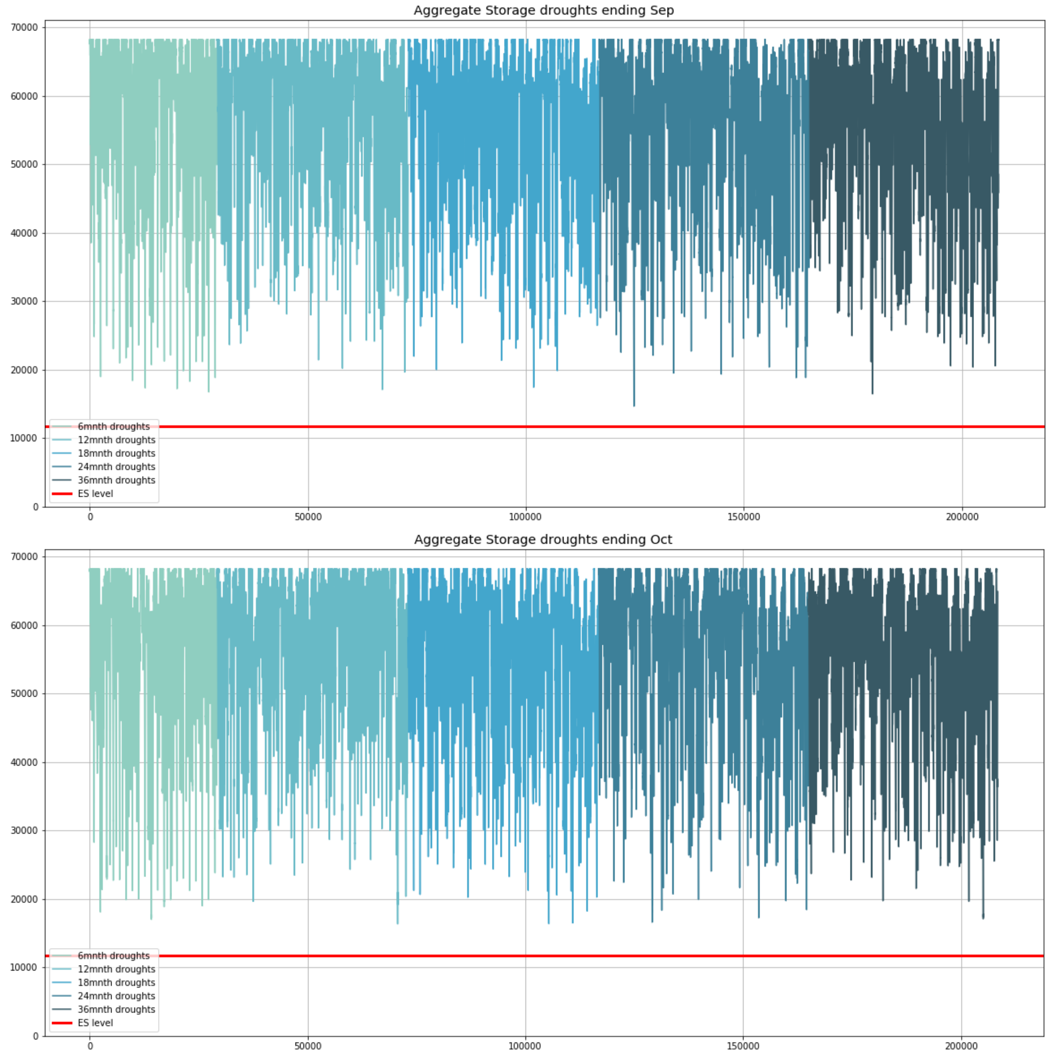


Figure 4-66 - Aggregate Drought Library Results for periods ending September and October

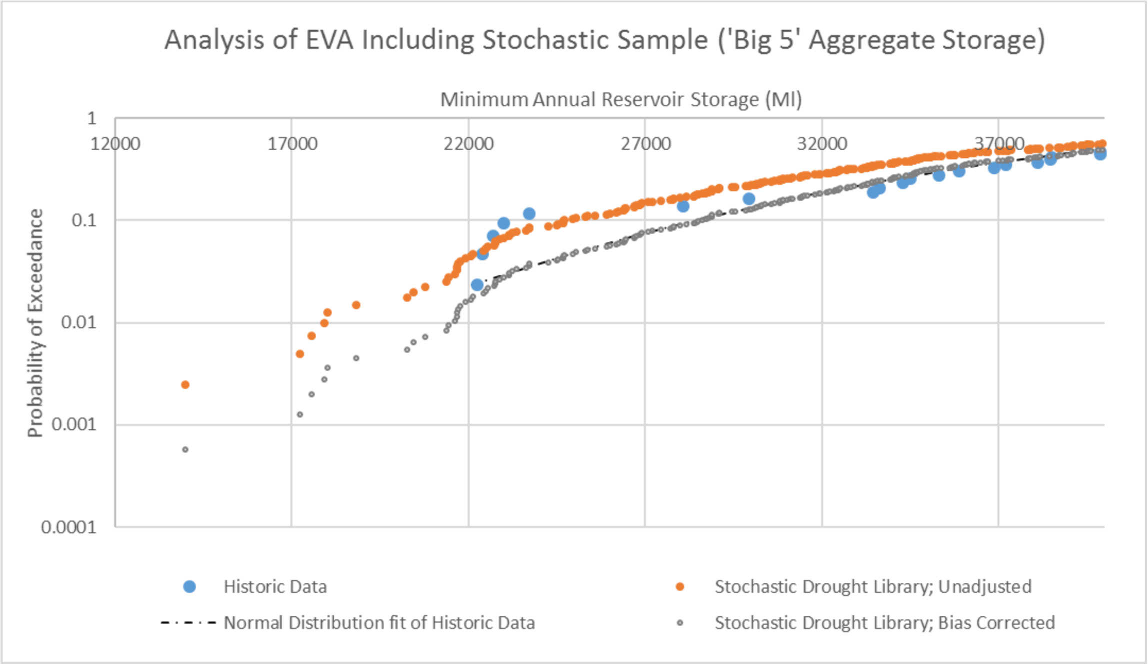


Figure 4-67 - Replication of the Resilience Testing Results from WRMP19

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

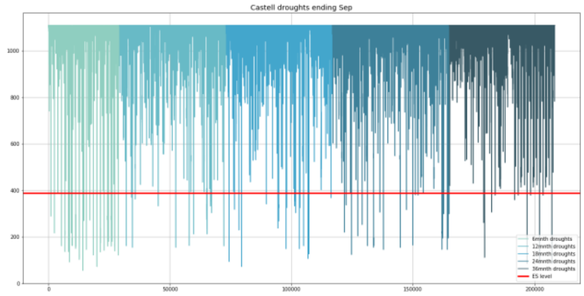
Reservoir	Cantref	Llwynon	Llandegfed	Usk	Ponsticill	Talybont
Emergency storage (Ml)	73.3	876	2733.2	4216	2513.3	1277.1
Number of failure days	0	475	0	2508	0	3240
Average duration (d)	0	23	0	29	0	64
Maximum duration (d)	0	51	0	91	0	208
Number of droughts with failure (/571)	0	24	0	102	0	51
Highest (most 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 4-68 below.



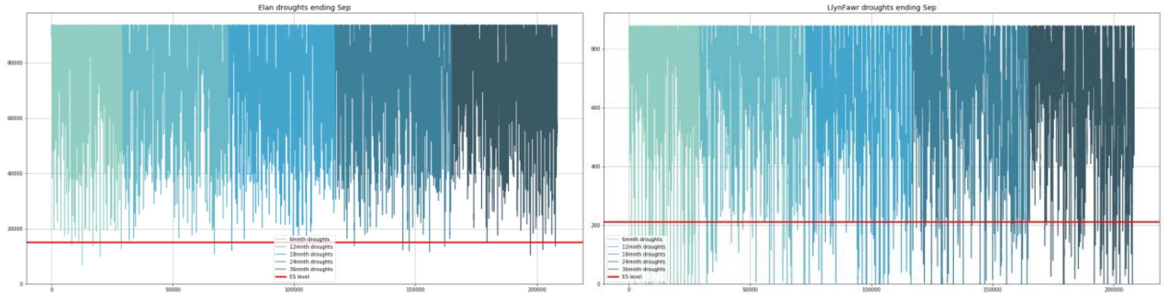


Figure 4-68 - Drought Library Results for period ending September for Castell Nos, (top left), Elan (bottom left) and Llyn Fawr (bottom right)

With the inclusion of climate change there are a handful of failures against aggregate emergency storage for the most severe events (see Figure 4-69). 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.

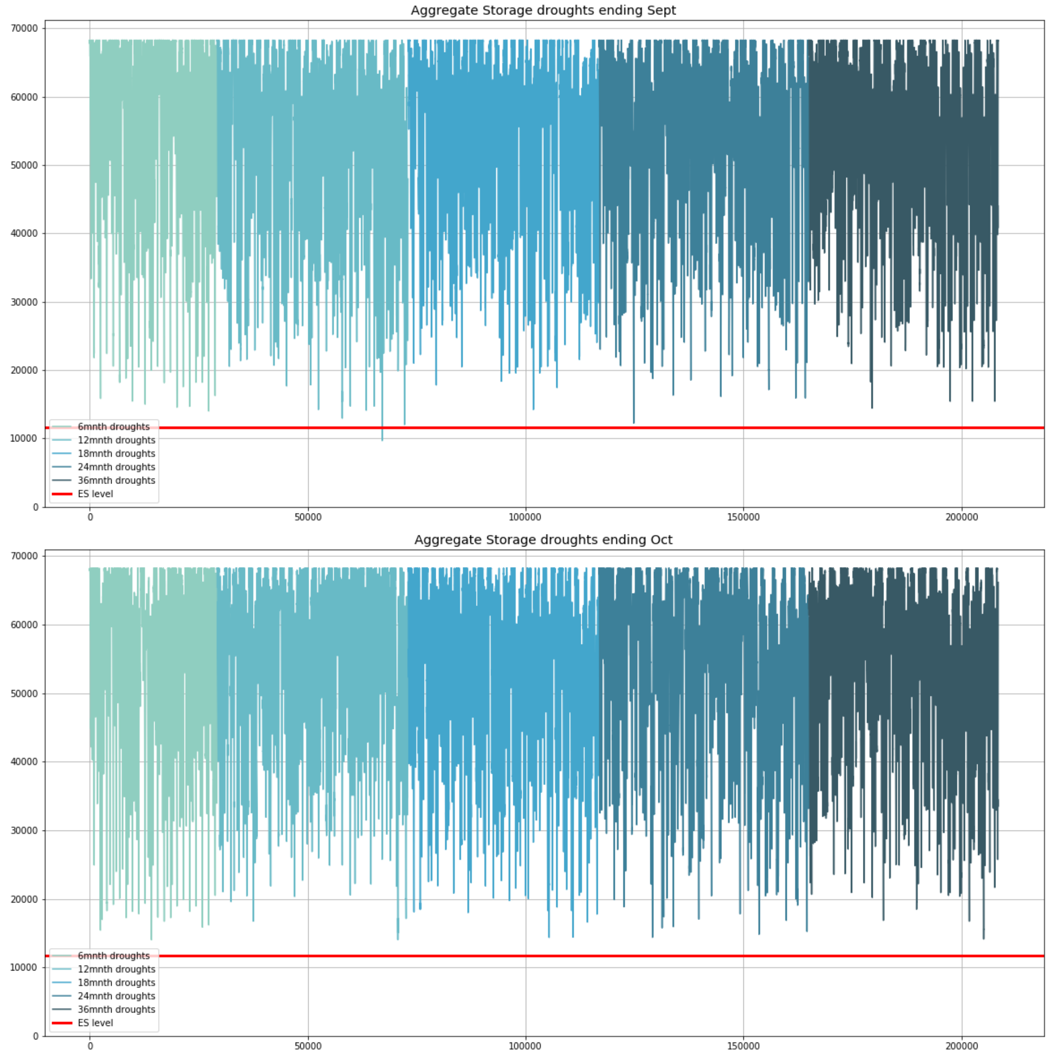
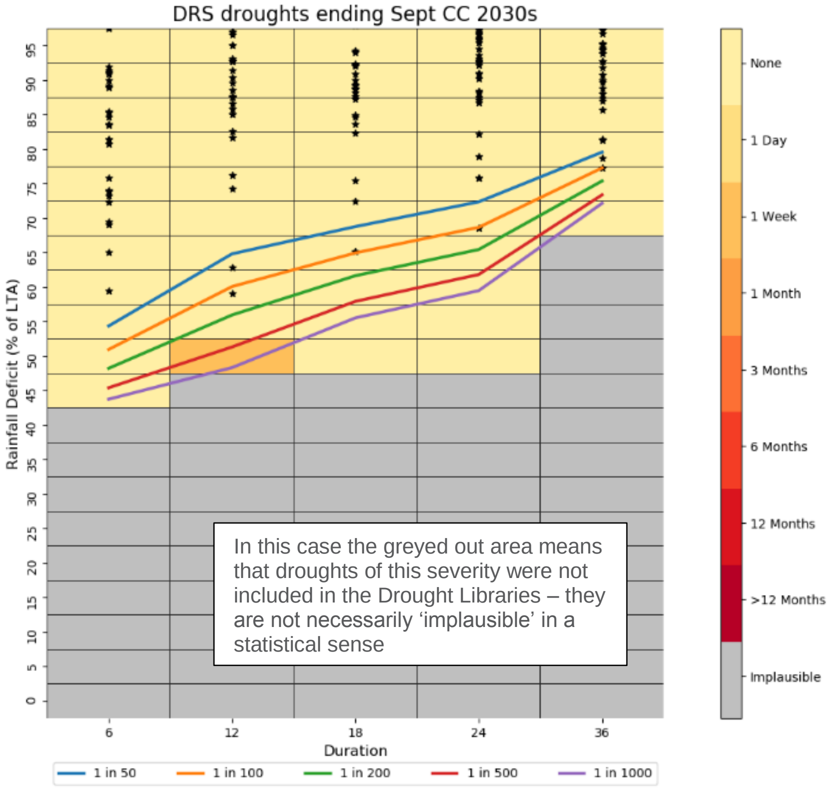


Figure 4-69 - Aggregate Drought Library Results for periods ending September and October with Climate Change

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 4-70 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).



In this case the greyed out area means that droughts of this severity were not included in the Drought Libraries – they are not necessarily ‘implausible’ in a statistical sense

Figure 4-70 - Drought Response Surface for ending September droughts with climate change

5. Conclusions

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.

6. References

Atkins (2016) Welsh Water WRMP19 Problem Characterisation Report

Atkins (2019) Drought Vulnerability Framework Hydrological Update

HRW (2017) DCWW WRMP19 Climate Change flow factors for water resources supply modelling

UKWIR (2017) Drought Vulnerability Framework 17/WR/02/12

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